Design of a Two Degree of Freedom Robotic Finger

A thesis submitted for the degree of
Master of Engineering (Mechanical)

by

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Abstract

The design of mechanical hands has been investigated at many universities. Most of the hands produced by their research have large actuator packs which are usually heavy and located remotely from the hand. They are also complex to control.

A number of robotic hand designs are reviewed and their shortcomings are discussed briefly. A feasibility study in 1993 at the University of Canterbury on a mechanically linked finger was used as the starting point for the design of a new finger – the Canterbury finger. Several combinations of electric drive motors, gearboxes, lead screws and mechanical linkages were examined before the final configuration was selected. The result is a human sized finger and hand capable of exerting a reasonable force at the finger tip, and able to curl through 180° in two distinct motions. While the dexterity typical of tendon operated fingers is retained, the new design avoids the elasticity and friction problems of tendon operated hands.

A single mechanically linked two degree-of-freedom (DOF) finger was designed, built and tested. The design and performance criteria were met, and the working finger provided insight into areas for improvement and future development. This thesis includes manufacturing drawings, test results, and basic control software for the Canterbury finger.

Acknowledgements

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Finally thank you to the staff and technicians who helped put the finger together.

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Nomenclature

Acronyms

A/D, ADC	Analogue-to-Digital Converter.
CAD	Computer Aided Design.
CAM	Computer Aided Manufacture.
CM	Carpometacarpal.
CNC	Computer Numerical Control.
D/A, DAC	Digital-to-Analogue Converter.
DC	Direct Current.
DIP	Distal Interphalangeal.
DPDT	Double Pole Double Throw.
DOF	Degree Of Freedom.
DSP	Digital Signal Processor.
EDM	Electrodischarge Machine.
EMG	Electromyographic.
IEEE	The Institute of Electrical and Electronics Engineers
IFToMM	International Federation on the Theory of Machines and Mechanisms
I/O	Input/Output.
IP	Interphalangeal.
MP	Metacarpophalangeal.
NC	Numerical Control.
PC	Personal Computer.
PCB	Printed Circuit Board.
PIP	Proximal Interphalangeal.
PWM	Pulse Width Modulation.
SMA	Shape Memory Alloy.
UPP	Universal Pulse Processor.

Symbols

α	helix angle of thread	°
η	screw Efficiency	%
η_B	motor Efficiency	%
η_{GB}	gearbox efficiency	%
θ	thread angle	°
θ_n	combined thread angle	°
σ_B	bearing stress on screw thread	MPa
σ_b	bending stress on screw thread	MPa
σ_{lug}	tensile stress in finger mounting lug	MPa
τ_{ave}	average shear stress	MPa
τ_{nut}	shearing Stress in threads of nut	MPa
τ_{sc}	shearing Stress in screw threads	MPa
A	area	mm²
A_{pin}	cross sectional area of a pin	mm²
b	thickness of the thread at the root diameter	mm
d, D	distance	mm
d_m	mean diameter of the screw thread	mm
d_{mb}	mean thrust bearing diameter	mm
d_o	the major diameter of the screw	mm
d_r	the root diameter of the screw	mm
f_b	coefficient of friction in the thrust bearing	
f_s	coefficient of friction in the screw	
F	force	N
F_N	normal force	N
F_T	force transferred to the finger tip	N
h	depth of thread	mm
I_B	current Demand	A
K_T	torque constant	mNm/A
L	length of the finger	mm
L_n	distance travelled on screw n for full travel of the lead screw nut $n = 1$ (bottom screw)	mm
L_I	distance travelled on screw 2 for full travel of the lead screw nut	mm

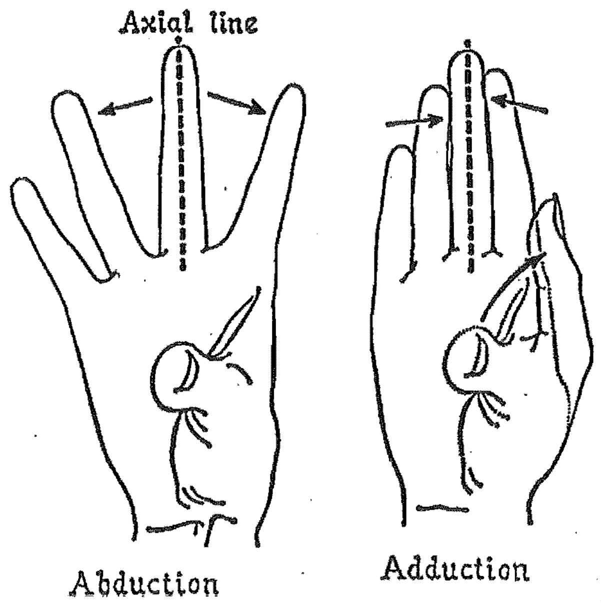
M	moment or torque	Nm
M_p	moment about point P	Nm
n	number of starts on the thread	
n_t	number of threads in nut	
N_0	no load speed	rpm
N_B	operating speed	rpm
N_{IP}	gearbox input speed	
N_{OP}	gearbox output speed	
p	pitch of screw thread	mm
P_{2B}	output Power	W
r, R	radius	mm
t_m	time taken for full travel of the finger	s
T_B	torque Output	mNm
T_f	friction torque	mNm
T_G	gearbox output torque	mNm
T_{out}	torque output	mNm
T_S	stall Torque	mNm
V	operating voltage	V

Abbreviations

act.	actuator(s).
anthrop.	anthropomorphic
approx.	approximately.
c.	circa.
deg.	degrees.
dia.	diameter.
ed.	editor.
max.	maximum.
min.	minimum.
op-amp	operational amplifier.
prelim.	preliminary.
v	version.

Glossary

Adduction / Abduction: to bring a limb, or any other body part towards (Adduction) or away from (Abduction) the body



[Basmajian & Slonecker, 1989]

Antagonistic relationship: pitting a pair of tendons against each other so that each opposes the action of the other.

Anterior: nearer to or at the front of the body; "in front of"

Anthropomorphic: having human like shape or form.

Carpus: the wrist.

Carpal Bones: the bones of the wrist.

Circumduction: movement of a segment so that its free end traces a circle in space; the segment describes a cone whose apex is attached to the end of the segment; a sequential combination of flexion, abduction, extension and adduction. The circular pitch/yaw motion of a finger, thumb, wrist or ankle (eye or head).

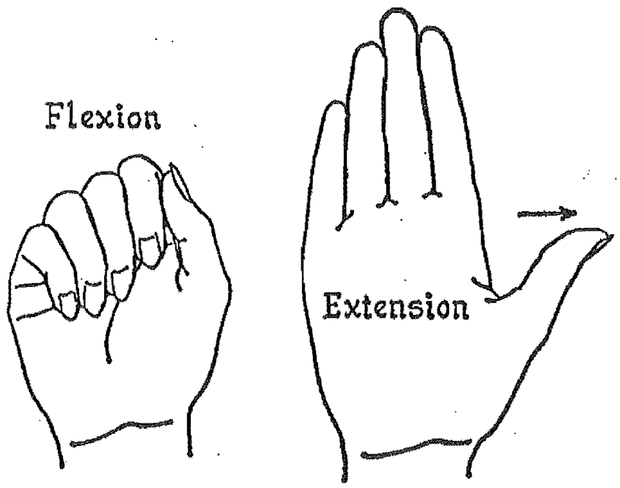
Dexterity: a combination of range of motion and location of singularities in the work volume; manual manipulative skill or adroitness; good physical co-ordination; physical, especially manual, skill or nimbleness.

Distal: far or farther from the trunk.

DOF (Degree of Freedom): the independent components of motion of a system.

Extrinsic: originating or acting from outside (*cf.* intrinsic).

Flexion / Extension: the act of bending (flexion) or, straightening or extending (extension), a limb.



[Basmajian & Slonecker, 1989]

Intrinsic: situated in or peculiar to a part (*cf.* extrinsic).

Medial: toward the mid-line of the body.

Metacarpus: the area of the hand between the wrist and the fingers containing the five metacarpal bones.

Opposition: a special motion in which the thumb touches the tip of a finger; a composite of circumduction and flexion of the thumb.

Palmar: of the palm of the hand.

Phalange: any bone of the fingers or toes (also Phalanx).

Pitch: up-and-down motion of the robot limb; Angular displacement along the lateral axis.

Posterior: nearer to or at the back of the body; "behind"

Proximal: near or closer to the trunk.

Radius: the inner of the two forearm bones.

Robot: a 20th century term originally meaning any mechanical man, it can mean any automatic device controlled by computer or remote control.

Roll: rotation of the joint about an axis that is in line with the arm; Rotation about the longitudinal axis.

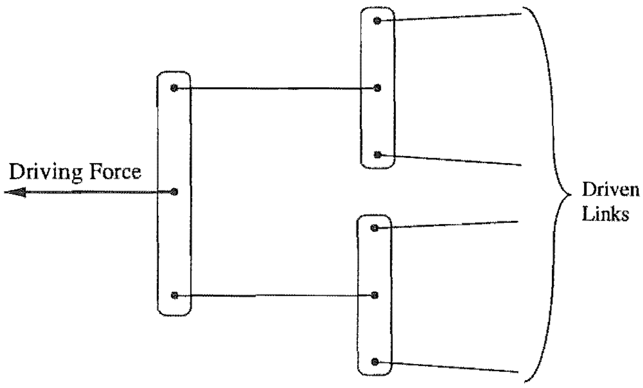
Servo Mechanism: an automatic control system in which the output is constantly or intermittently compared with the input through feedback so that the error or difference between the two quantities can be used to bring about the desired amount of control.

Singularity: the area in a robotic joint's range of motion that must be avoided because of mechanical or control defects; A point where a function ceases to be analytic, i.e. is not differentiable.

Teleoperation: operating a device by remote control.

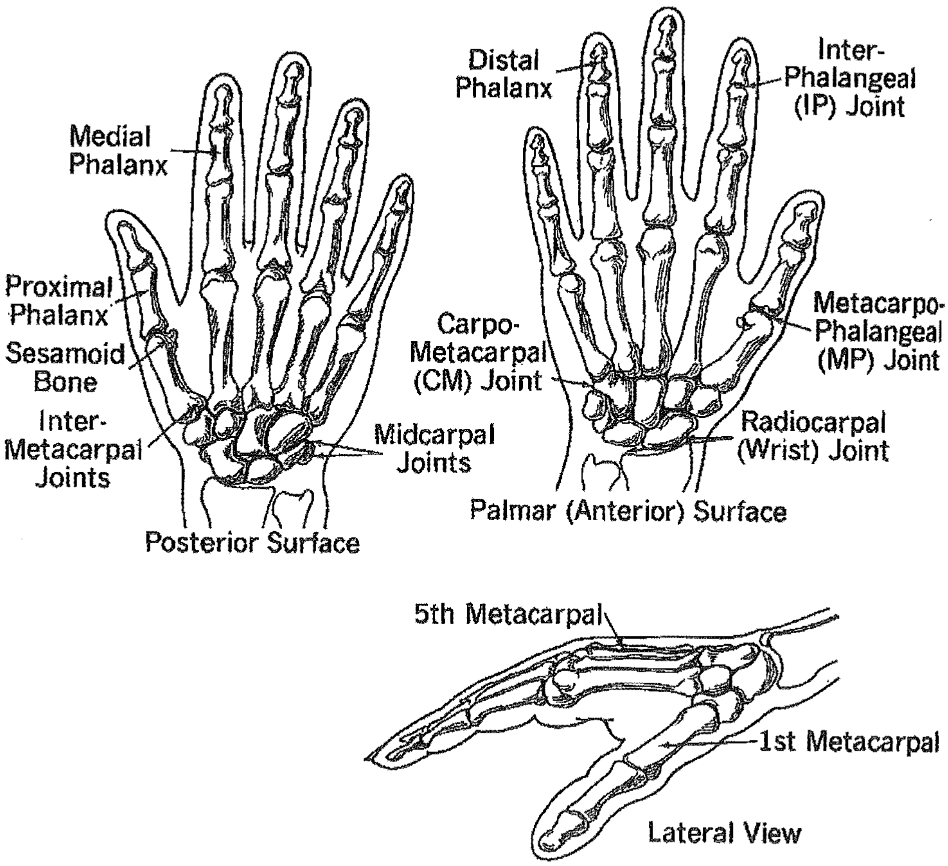
Ulna: the outer of the two forearm bones.

Whiffle Tree (Swingletree): a differential mechanism that spits one link into two or more new ones, while trying to maintain equal force in each of the two new links.



An example of a whiffle tree mechanism

Yaw: side-to-side motion of the robot joint; Angular rotation about a vertical axis.



Bone structure of the human (right) hand [Rosheim, 1994].

CHAPTER 1

Introduction

This chapter introduces the main aspects of the research presented in this thesis. The underlying aim is the design and construction of a two degree-of-freedom (DOF) robotic finger. The chapter provides an insight into the reasons behind this research, and what it has accomplished in terms of new contributions made to this field. The structure and scope of the material presented in the thesis is also outlined.

1.1 Field of Research

The general field of research of this thesis is multi-fingered multi-degree-of-freedom mechanical hands. There are two categories of the general field considered: robotic end-effectors and prosthetic hands. More specifically, this research covers the design and construction of a two degree-of-freedom (DOF) finger that, if linked with other similar fingers, can be assembled to form a mechanically linked anthropomorphic hand. This hand is intended for use as *either* a robotic end-effector *or* as a prosthetic hand. The research field pursued thus emanates from two quite diverse backgrounds with quite different objectives.

The human hand is extremely versatile and useful. Grasping, manipulating, pulling and pushing are just some of its capabilities. It can be used for tasks as diverse as heavy lifting and precision placement of small components. Each finger is a complex design that may offer four degrees-of-freedom, and is as complex as many robot arms.

For centuries people have tried to simulate its action, either for entertainment machines, such as the musician that was developed in the 18^{th} century as shown in Figure 1-1, or as a prosthesis for someone who has lost a hand.

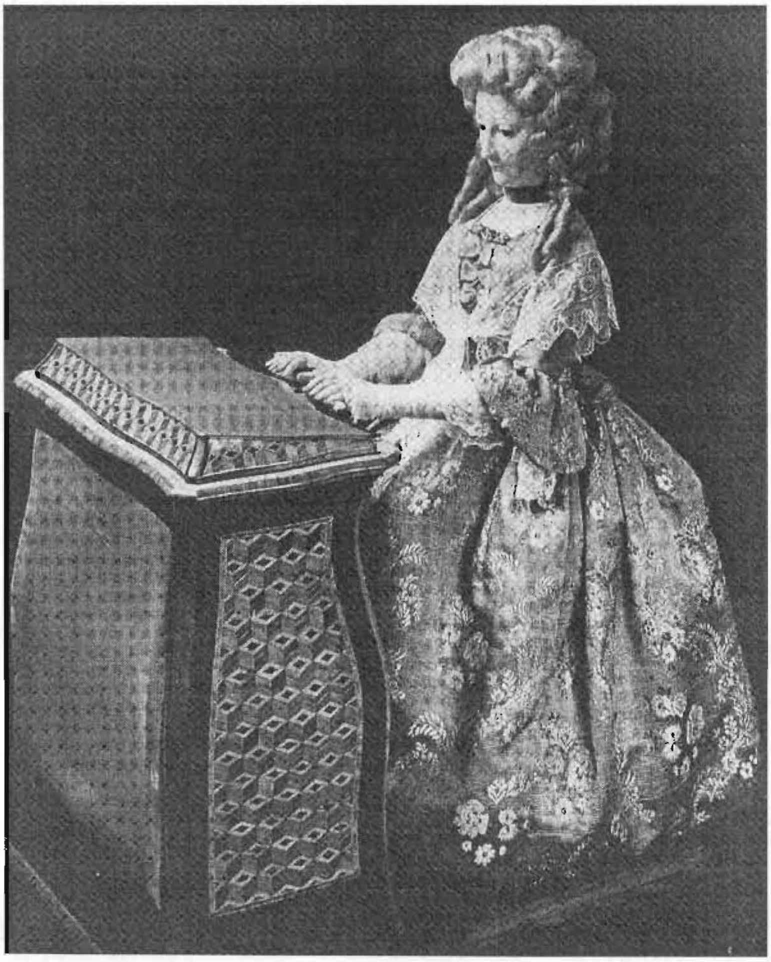


Figure 1-1 *Musician [Rosheim, 1994]*

Later on with the invention of robotic arms, the design of end-effectors led to the study of manipulation and to the development of robotic hands. However, as will be shown later in this thesis, the human hand is an extremely complex mechanism that is very hard to copy. It even incorporates its own lubrication and repair mechanisms.

1.1.1 Robotic End Effectors.

Ever since the first robotic arms were designed, engineers have been designing end effectors for them. Early examples were usually simple two jaw grippers, but these were quite restricted in the range of objects that they could grip. Generally a different gripper was required for each different object that was to be manipulated. Quick change grippers and turret grippers (Figure 1-2) were developed to try and overcome this limitation, but these were still not ideal. They only provided a simple and fast way to change the gripper between operations rather than performing general gripping operations. This desire for generalised end-effectors lead to the design and development of multi-finger, multi-DOF dexterous robot hands.

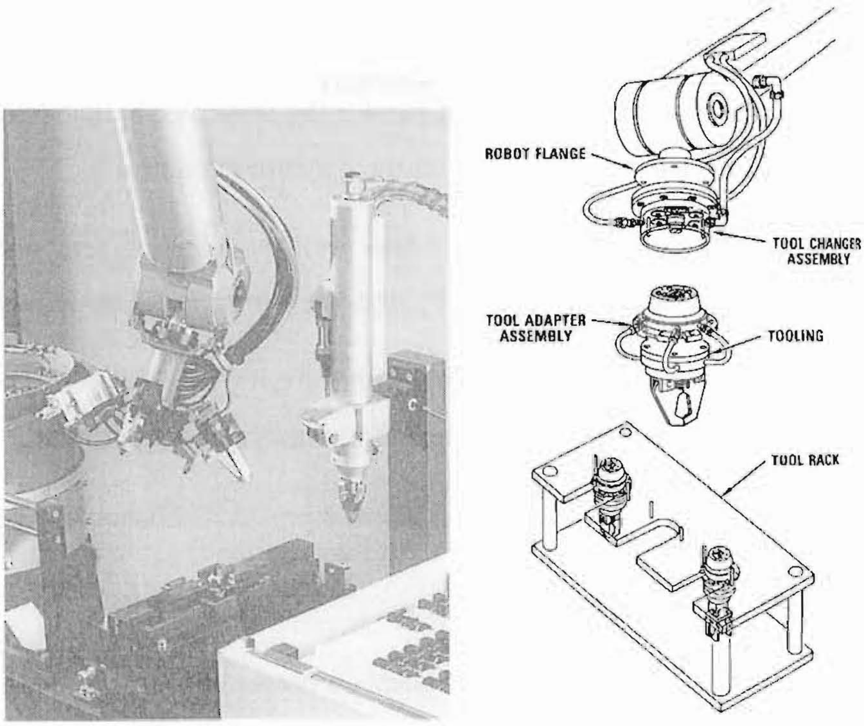


Figure 1-2 *A Turret Gripper and a Quick Change Gripper [Rosheim, 1994]*

Dexterous Robot Hands

The design of these dexterous hands followed two paths. Some designers modelled their designs on the human hand, producing what are referred to here as Anthropomorphic Hands, while others concentrated on the function of the hand and produced what is referred to in the following sections of this thesis as Robotic Hands.

Some of the advantages of these multi-fingered dexterous robot hands are:

1. They can readily accommodate a variety of tasks and objects.
2. They can cope with unforeseen situations.
3. They can work in unstructured environments - places where the tasks are initially undefined.
4. They have a higher grip stability than a two jaw gripper due to three or more object contacts.
5. Dexterous manipulation is possible. That is, it is possible to impart motions onto the gripped object by exerting appropriate finger forces.
6. It is possible to replace the operator in hazardous environments. For example Oomichi [1990] already has a hand that is capable of assembling and disassembling the 1500 lb (682 kg) check valves that are used in nuclear power plants.

Anthropomorphic Hands in robotic applications have some additional advantages:

1. It simplifies teleoperation if the robotic hand is the same as a human hand. The closer it is to the human hand, the easier it is for the operator to control it.
2. Where the environment requires human as well as robotic interaction. The same interface (e.g. valve, tool) can be used by both the human operator and the robot.

It is important to note however, that if a robot is only carrying out one or two clearly defined tasks, a custom designed gripper is more efficient at it's task, and easier to design and use than a multi-DOF robotic hand. [Bekey, 1990]

1.1.2 Prosthetic Hands.

Prosthetic hand design is a constant trade-off between power consumption, weight, size and performance [Hugh Steeper, 1993]. A prosthetic hand has to weigh a lot less than a human hand because it is not directly attached to the bone or muscles, and so is dead weight. In order that this dead weight is not increased unduly by a large battery, the prosthesis must have a very low power consumption. The shape and size of the prosthetic hand must also approximate that of the original hand. The more it looks like a human hand, the more comfortable the user will feel about wearing it.

The earliest mechanical limbs were described by the Ancient Greeks. Other examples exist from the 14^{th} century. Table 1.1 below outlines the development of prosthetic hands over the centuries.

Table 1.1 The development of prosthetic hands.

Ancient Greeks	Descriptions of mechanical limbs.
200 BC	Roman General fitted with iron hand.
14^{th} Century	Earliest existing examples of mechanical limbs.
1509	Spring loaded hand device built for knight, von Berlichingen.
1890s	Split Hook developed by D. W. Dorrance
19^{th} Century	First pneumatically powered hand.
1922	First electric hand.
1948	First myoelectric hand (Russia).
1949	Vaduz electric hand patented.

1955	First portable myoelectric hand design (Roehampton). (Earlier myoelectric amplifiers were too large to be portable).
1961	Kobrinski publishes a paper on the first EMG hand (Russian).
1965	Otto Bock Orthopaedic Industries develops an electric hand that grips with two fingers and a thumb.
1969	First Southampton hand - a four DOF hand with adaptive control.
1970	First commercial myoelectric hand.
1971-3	Simpson Hand (Scotland) - a gas powered hand for use by children.

As motors and batteries are made smaller, lighter and more energy efficient, designers are able to incorporate more degrees-of-freedom into prosthetic hands. Current research is concentrating on the control of these hands, reducing the number of inputs required from the wearer to make them less tiring to use, and making the method of control more natural. Some researchers are also starting to experiment with the feedback of sensation, e.g. heat or pressure, to the wearer. Although a simple control program is discussed in chapter 4, section 4.4, the control of prosthetic hands is not specifically covered here. This thesis concentrates on the mechanical design of an artificial hand.

1.2 Motivation for this Research

There are two main types of mechanical hands which may be suitable for either robot hands, or human prosthetic hands: cable operated hands, and linkage operated hands.

Most cable or tendon operated hands are not suitable for use as prostheses because of the large size of their driving mechanisms. Much research is however being done (as mentioned in section 1.1.2) in developing control systems for prosthetic hands, and using these research hands as development tools [Iberall et al., 1994]. This indicates that as soon as a suitable multi-DOF prosthetic hand is developed, an appropriate control system will have already been produced and can be immediately applied.

1.2.1 Robotic Hands

The robotic multi-fingered multi DOF hands that currently exist suffer from a number of limitations. Most have large heavy actuator packs, and this makes them more complicated to fit on the end of a robot arm. The cable operated hands suffer from frictional losses in the cables, and can be more complex to control because of the compliance in the cables or tendons. Many are also kinematically inefficient. The finger segments, or phalanges, usually pivot about an axis midway between their upper and lower surfaces, and the cables or linkages that curl the fingers act about this axis on the upper or lower surface. This effectively produces a very short lever, and hence a high transmission ratio, requiring a very high driving force to produce a reasonable force at the finger tip. The need for high driving forces requires a larger, heavier actuator package. The short levers also tend to accentuate backlash problems in linkage operated hands. Single DOF finger mechanisms also tend to complicate control issues, since the wrist of the robot arm must be accurately aligned when a grasp is initiated so that the target object can be grasped correctly by the hand.

The motivation here is therefore :

1. To produce a hand design that is compact and light weight so that it can be mounted complete with its actuator package on the end of a robotic arm.
2. To improve the kinematic efficiency by actuating the phalanges of the finger about an axis on their upper or lower surfaces.
3. To use a drive system that does not suffer from the frictional or compliance problems of current cable driven hands.

1.2.2 Prosthetic hands

Prosthetic hands can be classified as on of four types :

1. *Cosmetic.* These hands have no real movement, and cannot be activated, but they can be used for pushing or as an opposition element for the other hand.
2. *Passive.* These hands need the manual manipulation of the other (non-prosthetic) hand to adjust the grasping hand. These were the earliest hands, including the Berlichingen hand.
3. *Body Powered.* These hands use the motions of the body to activate the hand. Two of the most common schemes involve pulling a cable when the arm is moved forward (arm-flexion control) or pulling a cable when the shoulders are rounded (shrug control).

4. *Externally Powered.* These hands obtain their energy from a storage source such as a battery or a compressed gas cylinder. These are yet to displace body-powered hands as prostheses [Murray et al., 1994].

Most battery powered prosthetic hands are controlled using myoelectric signals (the electric signals caused by muscle activity) although some are controlled using a body powered switch. Even though a number of myoelectrically controlled electric hands are available commercially, mechanically controlled hooks are used by one in nine amputees in the United Kingdom [Hugh Steeper, 1993]. These electric hands have only one or two DOF, but do not give any force feedback to the user, unlike a body-powered device which does. The more useful designs tend to be the non-anthropomorphic hook designs. These body-powered hooks also tend to be a *lot* lighter than the electrically powered hands. The natural looking hands that have one DOF with fingers locked in a precision or chuck grip and can perform only a limited number of grasps [Kyberd & Chappell, 1994]. Figure 1-3 below shows some examples of some electrically powered prosthetic hands.

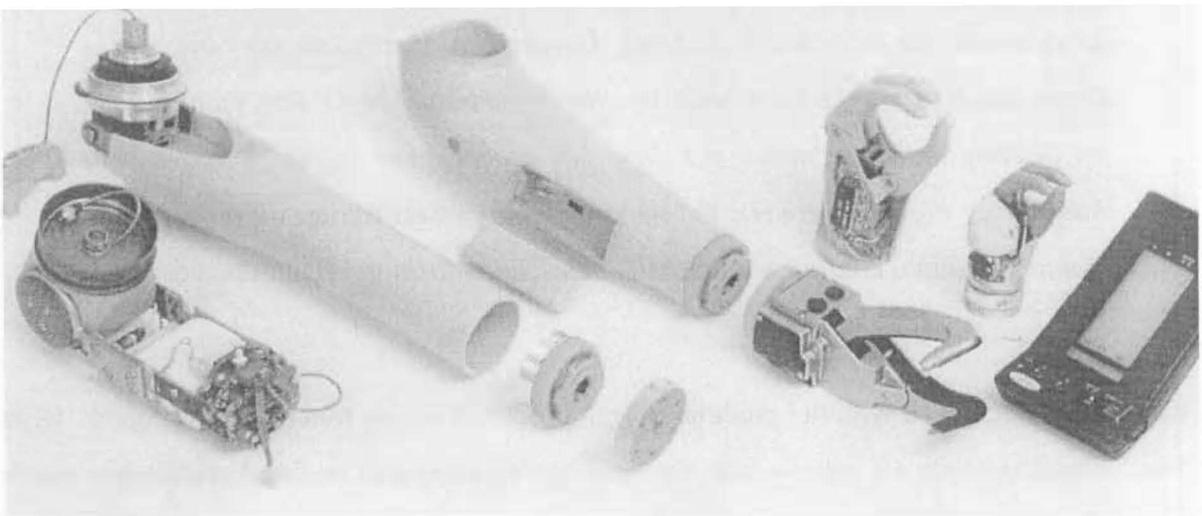


Figure 1-3 *Some commercially available prosthetic hands. [Hugh Steeper, 1993]*

Even the myoelectrically controlled hook shown in Figure 1-3 is quoted by Hugh Steeper [1993] as being much more useful than their anthropomorphic myoelectric hand designs. It also weighs 25% less, has a 75% greater force output, and moves twice as fast.

Aesthetics however, tend to be very important to the amputee. Many will put up with a less useful prosthetic device because it looks more natural. There are also many manipulations and grasps which are difficult, if not impossible, for a one or two DOF hand to perform.

The motivation then is to produce an anthropomorphic externally powered multi-fingered multi DOF hand that is light, powerful, easy to use, and which will perform many more grasps much more easily than current hands and hooks.

1.3 Contributions of this Thesis

This research covers the design and construction of a 2 degree-of-freedom (DOF) finger that, if linked with other similar fingers, can be assembled to form a mechanically linked anthropomorphic hand — the Canterbury hand. Two possible applications are seen for this hand. It could be assembled with four fingers and *two* thumbs for use as an end effector for a robotic arm, or with the more usual four fingers and one thumb for use as a prosthetic hand.

1.3.1 The Six-Fingered Hand

A six-fingered hand has been suggested for robotic manipulation.

> *The fingers at each end of the hand pivot to provide two opposed thumbs. A manipulator set of a thumb and two fingers can manipulate an object in a kinematically static fashion, with the other thumb and finger pair manipulator set coming into use when the first set reaches the limits of movement. Alternating the grip between the two manipulator sets allows an object to be manipulated in a continuous statically determined fashion.* [Dunlop and Ward, 1995].

This is simply achieved with the modular design produced during this research project. Being a hand intended solely for robotic use, the six-fingered hand will be fitted with larger motors to provide a more useful grip force. The larger motors will however add very little weight or space penalty.

The finger produced has its complete drive system housed in the metacarp, or palm, of the hand, producing a very light weight and compact package. It uses a solid linkage drive system to avoid the problems arising from frictional losses and compliance such as are suffered by cable driven hands. Also the phalanges are pivoted on their top surface, and actuated on their bottom surface to maximise leverage, and hence the kinematic efficiency, along the length of the finger.

1.3.2 The Prosthetic Hand

The hand produced is very similar in size and shape to a human hand. Each finger has two DOF allowing objects to be grasped even if the wrist is not exactly aligned for the task. This avoids gross movements of the shoulder and elbow while attempting to align the hand for the task, as can be necessary with some other prosthetic hands, and thus makes it much more natural looking in use. The current prototype finger, when assembled with other similar fingers, would produce a hand that is double the weight of an average human hand. However, it is expected that this could very easily be reduced to 1½ times the weight of the average human hand, with other weight savings being possible.

The work in this thesis has resulted in a finger that will give a hand that is aesthetically, dimensionally and operationally very similar to the human hand it is intended to replace. There is however some scope for improvement on this prototype design.

1.4 Thesis Outline

The material presented in this thesis follows a logical progression starting with a review of existing robotic hands and work by other researchers which provides the background for this research. The development work undertaken and the performance of the first prototype finger produced are described. Conclusions are then presented based on the research carried out and suggestions are made for further research. A glossary of non-engineering terms used is included, as is a list of bibliographic references to published works supporting the work presented here. A list of other references related to this research which were examined but were not directly referenced, is also included. The contents and scope of individual chapters in this thesis are described as follows.

In chapter 2 some of the historical hands are briefly introduced. A table summarising the hands that have been developed in more recent years follows. The remaining three sections carry more detailed descriptions of some of these hands with comments on the advantages and disadvantages of each particular design.

In chapter 3 the design of the Belgrade/USC hand is discussed in more detail. It is shown how this led to the concept for a new hand that would overcome some of the limitations of the Belgrade/USC design, which itself overcomes many of the disadvantages of other types of hand. Two French students, Laurent Magnier and Hugues Monier, who worked at the

University of Canterbury for Dr G. R. Dunlop on their undergraduate project, compared these ideas with cable and gear operated systems. The original conceptual design for the new finger mechanism was found to be superior, and their work is described. The multi-link design produced by these two students provided the basis for the work carried out by the author in developing a working finger.

The work carried out by Magnier and Monier [1993] provided a good basis for the development of a new hand that would overcome many of the limitations of the Belgrade/USC hand, as is discussed in chapter 3. Chapter 4 describes how that work was developed to provide a workable design for a new two DOF robotic finger. The component selection process is described, as are the important details of the design. The machining and production methods necessary to produce the finger are covered, and the finger control system that was used to test the first prototype is outlined.

The first prototype of the Canterbury finger was completed at the beginning of August 1995. Chapter 5 describes the performance tests carried out on the finger and discusses the results. The performance characteristics measured are compared with those calculated during the design phase. The performance of the Canterbury finger is also compared to that of some other hands, including the Belgrade/USC hand. Some of the limitations of the design are described and modifications that were made to the finger after it was built are also presented.

Chapter 6 summarises the research presented here, suggests improvements that could be made to the design, and discusses the merits of each. Suggestions for future research are then made.

The final chapter is followed by a bibliography of all the relevant literature read and includes two sections containing the addresses of the software and hardware manufacturers cited in the thesis.

CHAPTER 2

A History of the Hand

As described in chapter one, mechanical hands have been designed and built for over six centuries. In this chapter some of the historical hands will be briefly introduced. A table summarising the hands that have been developed in more recent years follows. The remaining three sections carry more detailed descriptions of some of these hands with comments on the advantages and disadvantages of each particular design.

The hands presented here can be divided up into three main groups as follows: Robotic Hands *and two classes of* Anthropomorphic Hands. Robotic hands *are multi-fingered multi-degree-of-freedom hands that have been developed for use as manipulators on robot arms. Although they may approach the functionality and dexterity of the human hand, they do not share its form and therefore can not be termed anthropomorphic.* Anthropomorphic hands *are differentiated from* robotic hands *because they resemble the form of the human hand, and can be divided into two groups: those where the fingers are operated by cables or tendons, and those where the fingers are either direct driven or operated by rigid links.*

2.1 Information Sources

The history of robotic hands is well reviewed by Rosheim [1994]. A large number of the illustrations in this chapter have been taken from Rosheim because it contained the best quality reproductions available for many of the hands reviewed. The appendices in MacKenzie and Iberall [1994] contain very good summaries of human upper limb anatomy, taxonomies of prehension, and prosthetic and robotic hands. The same authors have also produced a detailed review of human prehension [Iberall & MacKenzie, 1990]. The proceedings of the IEEE International Conferences on Robotics and Automation contain a large number of papers on robotic hands, especially from 1987 on.

2.2 The Human Hand

The human hand is a highly complex structure. It consists of five digits made up of a collection of bones, ligaments, tendons, fascia, and vascular structures encapsulated by skin. Thousands of sensors in the skin, muscles, and joints let the brain know its current state [MacKenzie & Iberall, 1994] e.g. joint angles, forces, and temperature. In this section the structure, capabilities and versatility of the human hand will be outlined.

2.2.1 The Structure of the Human Hand

The human hand consists of eight carpal (wrist) bones, five metacarpal bones in the palm, two phalanges in the thumb, and three phalanges in each of the four fingers. Figure 2-1 provides labels for the bones and joints in the hand.

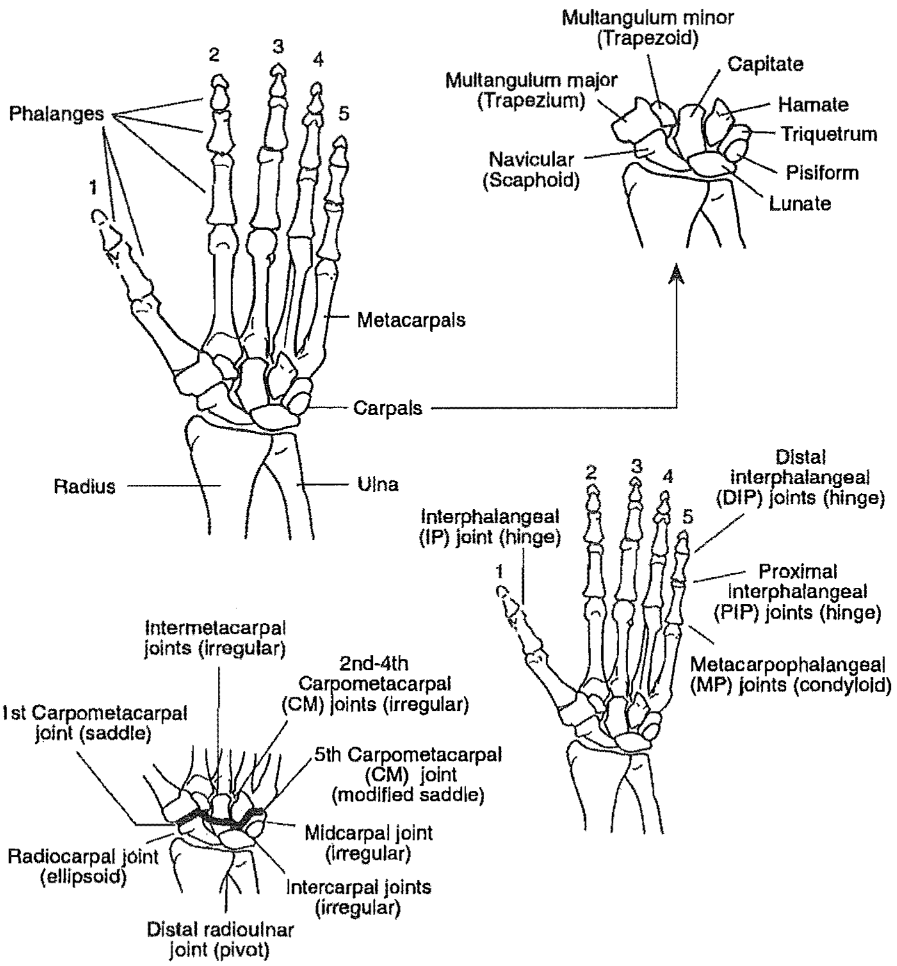


Figure 2-1 *The bones and joints of the human hand and wrist [MacKenzie & Iberall, 1994]*

The joints between the bones allow movement, according to the shape of the articulating surfaces, e.g. the heads of the bones. The structure and operation of the fingers is reasonably simple compared to the rest of the hand. The distal interphalangeal joints (the joints between phalanges, closest to the finger tip) and the proximal interphalangeal joints (the joints between phalanges, closest to the palm) are both simple 1 DOF hinge joints. The metacarpophalangeal joint (the joint between the body of the hand and the first, or proximal, phalange) is a 2 DOF condyloid joint that allows both pitch (flexion and extension) and yaw (adduction and abduction). The metacarpal bones are reasonably tightly constrained in the palm of the hand, but they do move a small amount as the hand is cupped, or as it conforms to an object that is being grasped. The carpal joints in the wrist are irregular and complex.

The fingers of the human hand are operated by two different sets of muscles. Extrinsic muscles (those located in the forearm) operate the fingers via tendons running in lubricated sheaths, and provide high power for grasping. Intrinsic muscles (those located in the hand itself) provide precision control, and curve the palm to wrap around objects being grasped.

2.2.2 The Mobility of the Human Hand

Different authors claim varying numbers of degrees-of-freedom for the human hand (as listed below), and this is because so many of the movements are so closely coupled that is difficult to distinguish between them.

Mobility :	21 DOF	[Shimoga & Khosla, 1994]
	22 DOF, 48 Muscles	[Andeen, 1988]
	20 DOF, 40 Muscles	[Rosheim, 1994]
	23+ DOF	[MacKenzie & Iberall, 1994]

MacKenzie and Iberall [1994] give the most comprehensive and accurate description, as reproduced in Table 2.1. Not including the wrist, they list more than 23 DOF for the human hand.

***Table 2.1** Degrees of Freedom of the Hand and Wrist [MacKenzie & Iberall, 1994]*

Bones	***Joints (type)***	***DOF***	***Motions***
Scaphoid, lunate & triquetrum (3 carpals)	radiocarpal (ellipsoid, synovial)	2	flexion & extension radial & ulnar deviation (abduction & adduction)
Carpals	midcarpal joint & intercarpal joints (irregular, many planar, synovial joints)	1 2-3?	flexion & extension radial & ulnar deviation rotations?*
Metacarpals	1st carpometacarpal (saddle, synovial)	3	flexion & extension abduction & adduction internal & external rotation†
	2nd & 3rd carpometacarpal joints (irregular, synovial)	little	
	4th carpometacarpal (irregular, synovial)	1	flexion & extension
	5th carpometacarpal (irregular, synovial)	2?	flexion & extension abduction & adduction
	4th & 5th (+ other) intermetacarpals (?, synovial)	1?	N.B. with 5th metacarpophalangeal abducting? or cupping?
Phalanges	1st metacarpophalangeal (condyloid, synovial)	2	flexion & extension abduction & adduction
	2nd & 3rd metacarpophalangeal (condyloid, synovial)	2+	flexion & extension abduction & adduction slight cupping‡
	1st interphalangeal (hinge, synovial)	1	flexion & extension
	2nd - 5th proximal interphalangeal (hinge, synovial)	1	flexion & extension§
	2nd - 5th distal interphalangeal (hinge, synovial)	1	flexion & extension**

The mobility (range of movement) of the individual joints are also high. Rosheim [1994] quotes joint mobility for the human hand as being:

Fingers	90° pitch (flexion & extension)
	25° yaw (abduction & adduction - MP joint)
Thumb	90° pitch (flexion & extension)
	45° yaw (abduction & adduction - CM joint)

* There are inter-dependent motions about the radiocarpal, midcarpal and intercarpal joints.

† Rotation is coupled to flexion & extension (due to ligaments).

‡ Possible only in extension

§ There is coupling on the extension of fingers 3 & 4 and individual differences in the independence of finger 5.

** There is limited independence of fingers 3, 4 & 5, with large individual differences.

This degree of articulation is very difficult to reproduce in an artificial hand.

2.2.3 Hand Vital Statistics

To compare the human hand to robotic hands we can put the performance and dimensions of the human hand into engineering terms. This section quantifies parameters of the human hand and comments on the difficulty in achieving them in an artificial hand.

Hand Dimensions

Vanriper et al. [1992] quote the average maximum dimensions of the human hand as being:

Length = 190 mm

Width = 90 mm

Depth = 28 mm

These values correlate well with the dimensions of various human hands observed during the course of this study.

Speed

Finger tapping rates of up to 10 Hz have been recorded [Bekey et al., 1990], but the time taken for the finger to pass through its full range of movement and return to its initial position is approximately 0.3 s.

Strength

Although in some cases the human hand is so strong that a person's entire body weight can be suspended by one or two fingers, Kyberd [1995] has stated that 80% of grips only require a 10 N force. Nieman [1990] lists the grip strength of the average male aged from 20 – 39 years as being 106 – 112 kg (1040 – 1100 N) and of the average female for the same age group as being 61 – 64 kg (600 – 630 N). However this force is measured between the second or proximal interphalangeal (PIP) joint of the fingers and the palm and so cannot be compared to most of the data we have for mechanical hands where the force is measured at the finger tip.

Weight

The average weight of a human hand disarticulated at the wrist (i.e. including the carpal bones) is 400 - 500 g [Love, 1996]. A direct comparison with a robotic hand would require that the weight of the extrinsic muscles (the muscles located in the forearm that provide much of the power for grasping) be included in this total, but in the case of a prosthetic device, some amputees will retain much of this forearm muscle, and so the prosthesis should only weigh the same as the actual hand that it is replacing. However this is still not really an applicable target weight for a prosthetic hand, since any prostheses will appear as dead weight, not held by tension in muscles or being attached directly to the bones of the forearm. A prosthetic device should therefore be lighter than a human hand.

Dexterity

Dexterity is difficult to quantify. Generally when designing anthropomorphic mechanical hands, the dexterity of the human hand is the highest that can be achieved, and is what is aimed for. An estimate of the dexterity of a robotic hand would be the number of degrees of freedom it possesses. The higher the number of degrees of freedom, the higher the dexterity of the mechanical hand. By this definition the dexterity of the human hand is very high, since the human hand has over 23 DOF.

Method of Operation

The hand is operated using high power muscle groups in forearm (extrinsic muscles) via tendons, and directly using low power muscle groups (intrinsic muscles) in hand for precision control.

2.3 Early Mechanical Hands

Entertainment robots have been in existence since the time of the Ancient Greeks when the engineer Ctesibuis (c. 270 B.C.) built organs and water clocks with moving figures. Later jacquemart, or Jack figures appeared on medieval clocks, for striking the hours. In the mid 1700s a Swiss craftsman, Pierre Jaquet-Droz (1721-1790), built a number of extremely intricate mechanical figures. One, the Musician (Figure 1-1) possessed two articulate five digit hands and played the organ. The hands were powered and controlled by pinned cylinders in the Musicians body [Rosheim, 1994]. Figure 2-2 shows the system of cranks and linkages that operates the fingers of the Musicians hand.

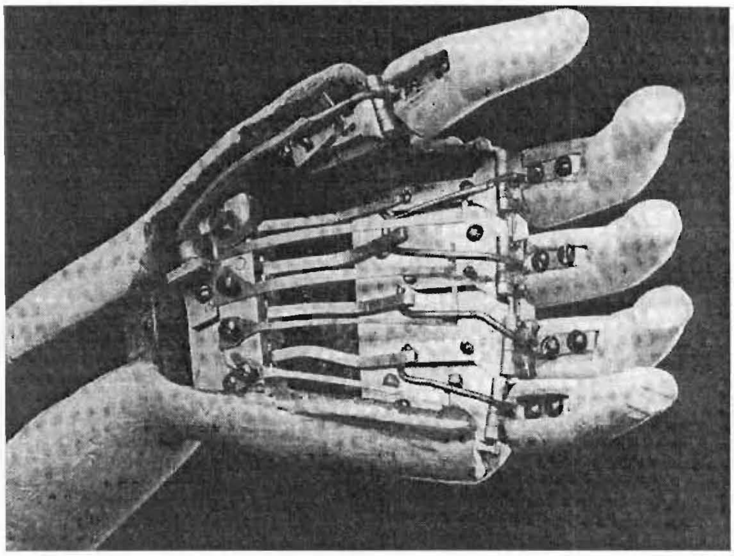


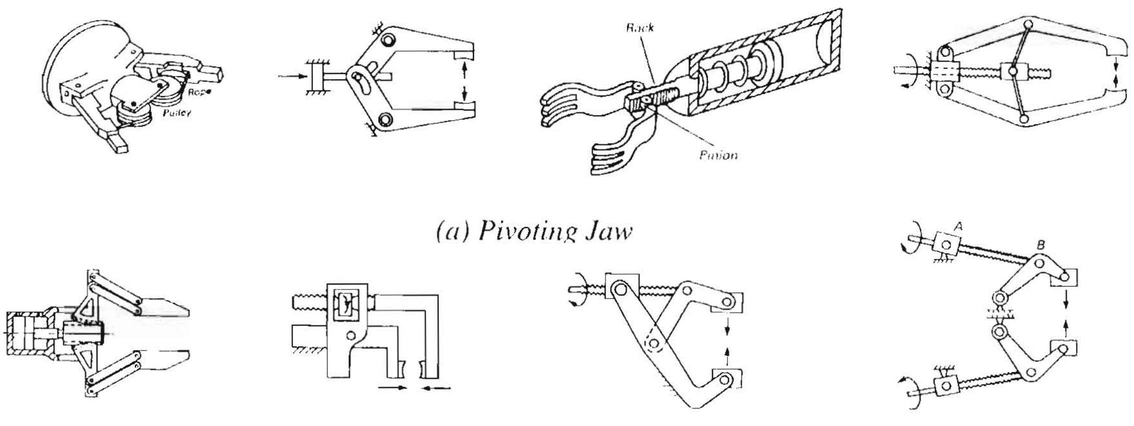
Figure 2-2 *The Musician's Hand. [Rosheim, 1994]*

The first uses of multi-fingered hands however, were as prosthetic devices to replace lost limbs, the history of which has already been outlined in Table 1.1.

With the advent of robots the need for an end-effector or "hand" on the end of a mechanical arm lead to the development of robotic grippers.

2.3.1 Robotic Grippers

The first robotic end-effectors were simple one or two DOF grippers. Many ingenious designs have been developed. Some are fingered grippers, as shown in Figure 2-3, others use vacuum cups or magnets to grip onto the target object. Each gripper however is quite task specific and are usually only designed to manipulate one particular object.



(a) Pivoting Jaw

(b) Parallel Jaw

Figure 2-3 *Some typical robot grippers [Pham & Heginbotham, 1986]*

As mentioned in section 1.1.1, in order to try and get around the limitations of these task specific grippers, turret and quick change grippers were developed, but these only provided a quick way to change to another customised, task specific gripper. A more attractive solution was seen to be the development of dexterous end-effectors that could perform many different tasks easily.

Table 2.2 *Comparison Different of Hands*

HAND	**Number of Fingers**	**Number of Thumbs**	**DOF**	**Cosure Time**	**Weight**	**Section in Thesis**
Canterbury (robotic)	4	2	15	1.05 s	1.2kg	Chapter 3
Canterbury (prosthetic)	4	1	12	1.05 s	1.0kg	"
Robot Hands						
CTSD I	3	None	1			2.4.1
CTSD II	2	1	3			"
GE Handyman	2	None	6			2.4.2
Karlsruhe	3	None	9			2.4.3
Odetics	1	2	8			2.4.4
Sarcos	2	1	3			2.4.5
Skinner Hand (MPMS)	3	None	5+			2.4.6
U.K.	3	None	9			2.4.7
USTB	1	2	8		3 kg	2.4.8
Cable or Tendon Operated Anthropomorphic Hands						
Anthrobot-2	4	1	16		4.5 kg	2.5.1
Belgrade Prosthetic	4	1	1			2.6.1
Hitachi	2	1	12	90 °/s	4.5 kg	2.5.2
Jameson	3	1	?			2.5.3
JPL	3	1	16	~ 1 s	0.9 kg*	2.5.4
Mitsubishi Heavy Industries	3	1	14			2.5.5
Salisbury	2	1	9		6.6 kg	2.5.6
Utah/MIT	3	1	16			2.5.7
Victory Enterprises	3	1	?			2.5.8
WABOT-2	4	1	14		0.45 kg*	2.5.9
Direct Driven Anthropomorphic Hands						
Belgrade/USC (model I)	4	Fixed	2	~ 2 s		2.6.1
Belgrade/USC (model II)	4	1	4	~ 2 s		"
Belgrade/USC (model III)	4	1	6	~ 1 s		"
Omni-Hand	2	1	9	1/2 "/s		2.6.2
Southampton	4	1	4			2.6.3
Human Hand	4	1	23+	0.3 s	0.4-0.5 kg	2.2

* The weight listed for the JPL and WABOT-2 hands is only for the hand itself and does not include the weight of the actuator pack.

2.4 Robotic Hands

In order to introduce some flexibility into robot operations, many robotic hands have been developed to replace a task specific gripper that must be changed if the robot is required for some different task. Some examples of non-anthropomorphic hands that have been developed follow in the next sections. In some cases a non-anthropomorphic design was chosen because of limitations in power pack technology, and in other cases it was chosen to try and give the hand greater flexibility.

2.4.1 Crew and Thermal Systems Division (CTSD) Hands

Two versions of this non-anthropomorphic hand were developed at NASA's Johnson Space Centre by the Crew and Thermal Systems Division (CTSD) in the 1980s [Rosheim, 1994]. The first version of this hand, the CTSD I hand, had only 1 DOF. The fingers, spaced 120° apart, were held open by a spring and actuated by a cable being wound onto a drum. The mechanism is arranged so that if one finger stops, the others continue to close in a simple, differential manner. This hand is however restricted to simply grasping objects, not manipulating them.

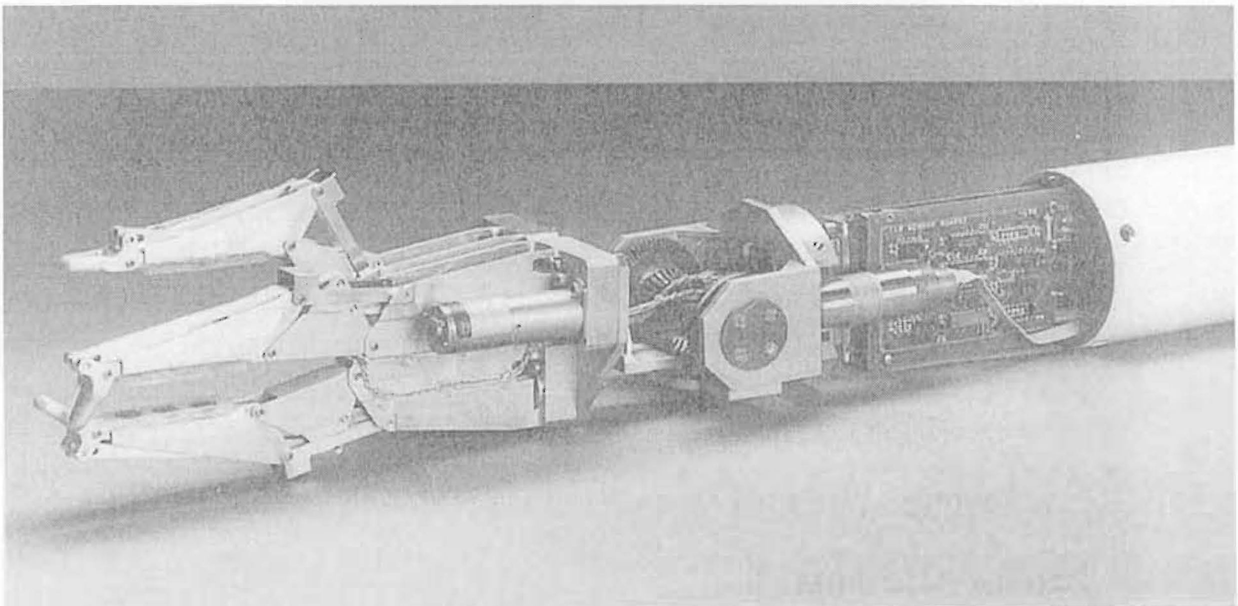


Figure 2-4 *CTSD II hand [Rosheim, 1994]*

The CTSD II hand (Figure 2-4) adds two more motors to form a three DOF hand. The finger arrangement is also changed slightly to form a two fingers opposing one configuration that provides parallel grasping surfaces. Tactile sensing has been added to the hand to provide force feedback, and the drives do provide grip force control, however this hand is still very limited in the grasps and manipulations it can perform.

2.4.2 General Electric Handyman Hand

This is an articulated electro-hydraulic multi-jointed hand designed by Ralph Mosher for the General Electric (GE) Handyman, an early 1960s teleoperated robot [Rosheim, 1994]. As seen in Figure 2-5 it has two 3 DOF fingers that attach directly to the robots forearm. It featured force reflection which made it possible for the operator to do things such as wielding a hammer and twirling a hula hoop. The fingers are driven by steel tendons which, like in similar tendon driven hands, have the tendency to break unpredictably. Tendons are difficult to replace remotely, which is a big disadvantage for a robot designed for the nuclear industry.

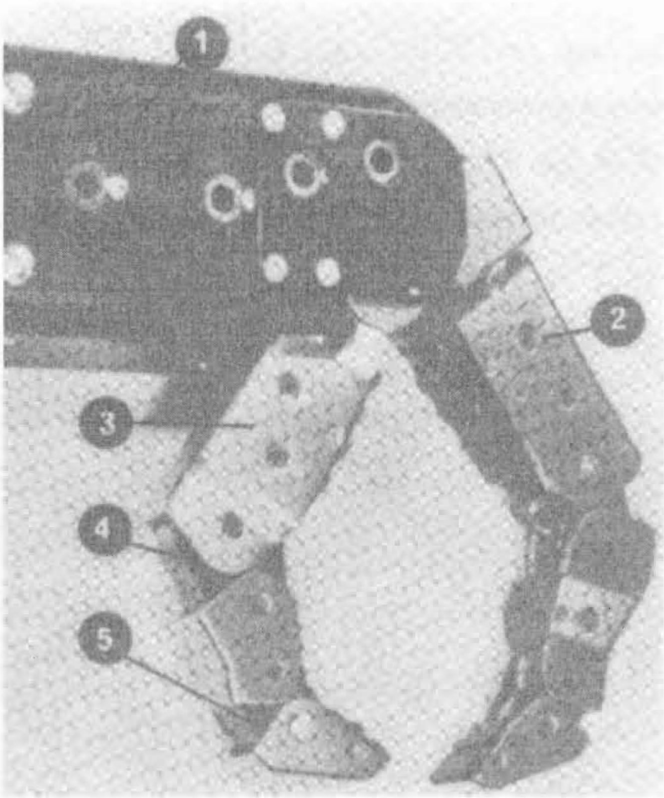


Figure 2-5 *General Electric Handyman hand [Rosheim, 1994].*

2.4.3 Karlsruhe Hand

The Karlsruhe Hand [Wöhlke, 1994] is a three fingered non-anthropomorphic hand that has been in development at the University of Karlsruhe since 1988. The fingers are arranged symmetrically about a central axis. Each finger has three DOF, with the first (proximal) link of the finger being direct driven via harmonic drives for both pitch and yaw, and the second, or distal, link being driven via another harmonic drive and a steel reinforced timing belt, as can be seen in Figure 2-6.

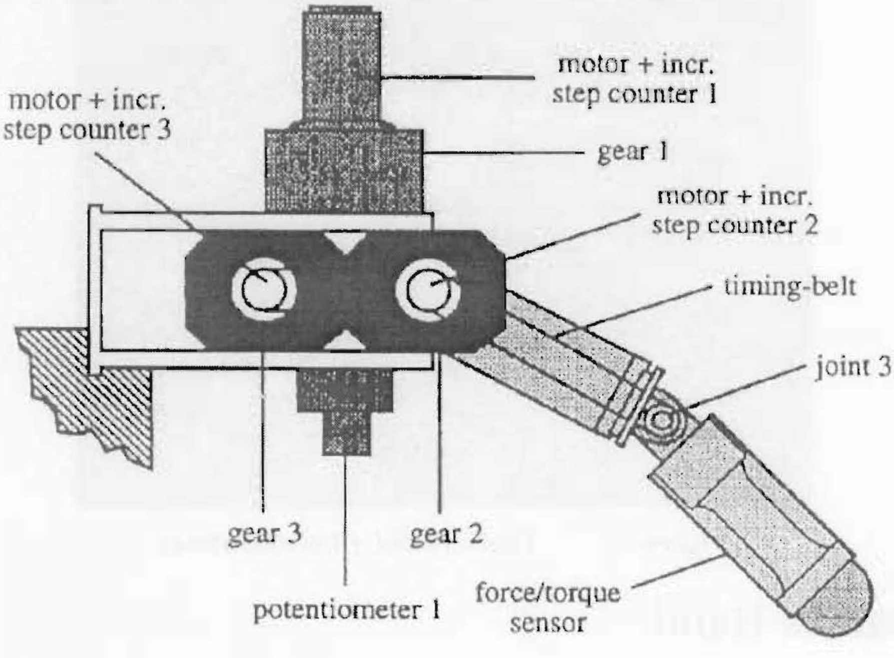


Figure 2-6 *A finger from the Karlsruhe Hand [Wöhlke(1994)].*

It features a 6 DOF force/torque sensor, and a tactile finger tip sensor and is being used to investigate dexterous grasping and manipulation. Each finger is controlled by a separate Motorola 68020 microprocessor, and the fingers are co-ordinated by a third 68020 microprocessor. The direct drive method used gives good performance, while minimising the effects of friction and compliance that cause problems in cable operated hands.

2.4.4 Odetics Hand

The Odetics hand (Figure 2-7) is a simple hand with one finger and two thumbs. Other than some publicity material, very little information has been released on this design [Rosheim, 1994]. The fingers are driven via a two speed transmission and clutch mechanism, and incorporates some force sensing to provide the hand with two speed modes. The fingers are driven fast until they make contact with the object being grasped. They then change into their low speed mode to increase the grip force. Each finger has a drive motor and a solenoid. When the solenoid is energised, the fingers rotate on their base, and when it is locked the upper finger knuckles are driven. Dexterity is quite low however, because of the simple kinematics.

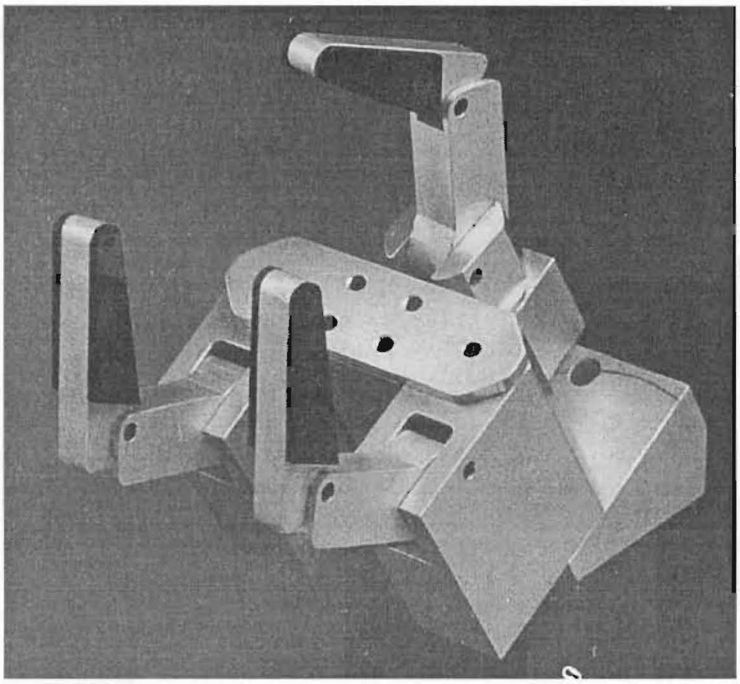


Figure 2-7 Odetics hand [Rosheim, 1994]

2.4.5 Sarcos Hand

Hydraulically powered, this hand has a very high load capacity of 22.7 kg. It is a three fingered, three degree of freedom hand. Although it is seemingly capable of an impressive range of grasps, it still does not rival the kinematics and degrees of freedom of the human hand. It resembles the form of a split hook prosthetic hand with a curved, fixed index finger, another finger capable of adducting and abducting, and a 2 DOF thumb that flexes, extends, adducts and abducts. The hand is fitted with a 3 DOF wrist to help make up for its limited dexterity.

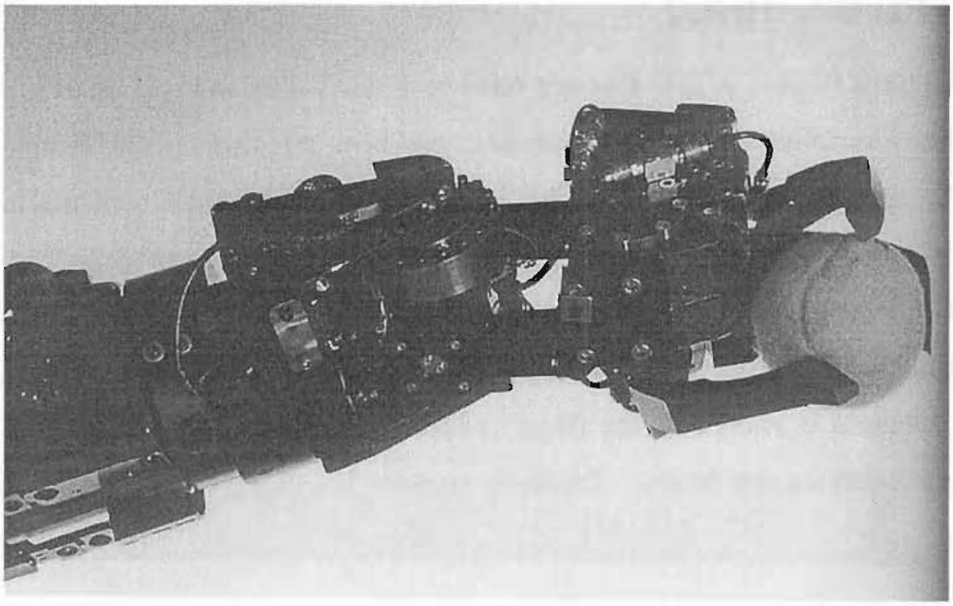


Figure 2-8 Sarcos hydraulically powered hand [Rosheim, 1994].

2.4.6 Skinner Hand

The Skinner hand, or multiple prehensile manipulator system (MPMS) [Andeen, 1988], was developed in the early 1970s for industrial assembly [Venkataraman (1990b)], and funding was provided by NASA to develop it for use in Skylab [Rosheim, 1994]. It uses three multi-articulated fingers (made up of three links each) as shown in Figure 2-9, and has at least 5 DOF with at least two of the fingers being able to rotate as well as flexing and extending. Even with its simple design it is able to perform most of the six prehensile patterns of the human hand.

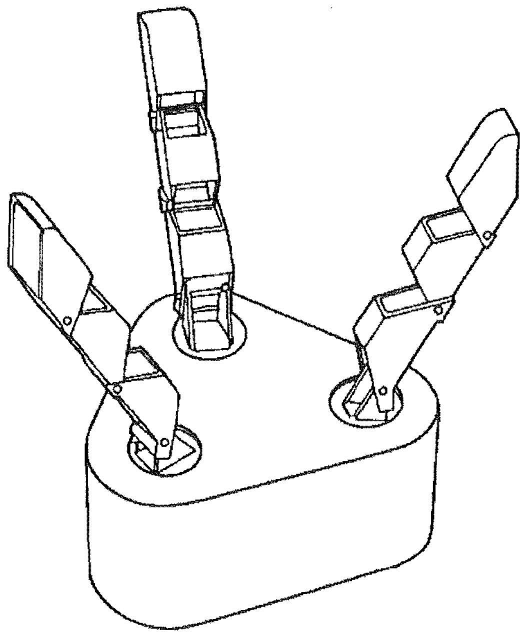


Figure 2-9 *Skinner hand [Andeen, 1988]*

2.4.7 U.K. Hand

This three fingered 9 DOF cable operated hand was developed by Guo et al. [1991] after studying the Utah/MIT, Salisbury, and Belgrade/USC hands. A mechanism has been proposed that improves upon currently available dexterous hands in four areas:

(i) *assembly functionality* – each finger is fitted with a rotating fingertip to turn grasped objects in assembly tasks. This allows more complex manipulations to be performed by the hand, two examples of which are shown in Figure 2-10.

(ii) *cable interference* – the mechanism is designed so that adduction and abduction of the finger does not affect the length of the cables operating the proximal and distal links of the finger. Compensation that is required in other hands, is therefore not required here.

(iii) *number of actuators* – actuation has been achieved with N independent actuators for N independent DOF, rather that N+1 actuators (Salisbury hand) or 2N actuators (Utah/MIT hand), minimising the number of actuators required.

(iv) *actuation coupling* – the motion of each joint is controlled independently of the others unlike tendon operated hands like the Salisbury hand where the actuators co-operate to manipulate each joint. This simplifies control greatly.

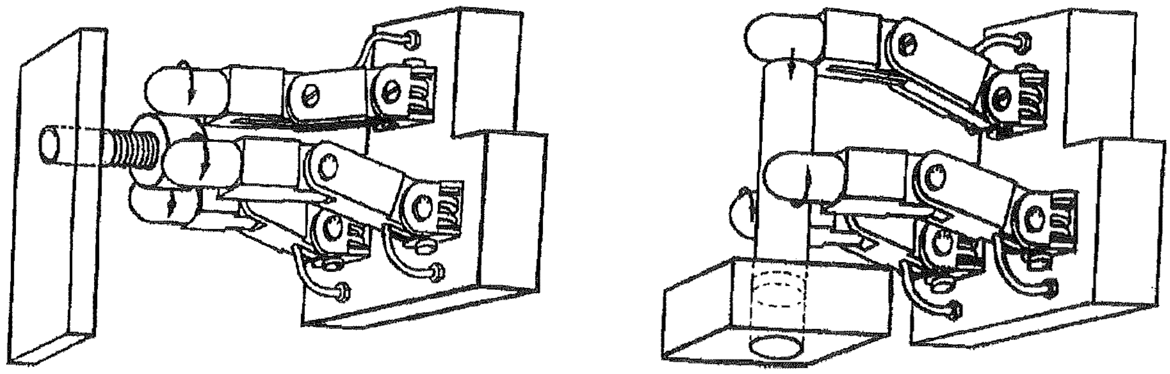


Figure 2-10 *The U.K. Hand, showing the advantages of its rotating finger tips [Guo et al., 1991]*

2.4.8 University of Science and Technology, Beijing (USTB) Hand

The USTB hand [Congqinq et al., 1993] is a non-anthropomorphic hand based on the Belgrade/USC hand. It has been jointly designed by Robotics Research Institute, University of Science and Technology, Beijing (USTB), and the Institute of Robotics and Intelligent Systems, University of Southern California (USC). The hand has three fingers: two 3 DOF thumbs, and a 2 DOF middle finger. The thumbs rotate 90° about an axis parallel to the centre line of the hand, and all three fingers adduct, abduct, flex and extend. All three fingers have two additional dependent DOF allowing the fingers to curl when flexing and extending. These two dependent DOF also incorporate self adaptability – when the first phalange contacts the object being grasped, the others keep moving until they also make contact. Steel cables are used to transmit the power to the fingers.

Although it can perform eight standard grasps the USTB hand still has much lower dexterity than the human hand and can only perform simple manipulation and assembly tasks.

2.5 Cable or Tendon Operated Anthropomorphic Hands

The hands described in the following section are cable or tendon operated, and are anthropomorphic (i.e. they resemble the form of the human hand). The cables or tendons run from a group of actuators mounted in the forearm, or further away, through the wrist to each independent joint. The main problem with cables and tendons is the elasticity of the cable or tendon, and for hands using Bowden cables, the frictional losses caused by the inner cable running on the outer sheath. The cables also tend to stretch over time requiring adjustment and recalibration of the hand. The actuator packs used in these hands are often heavy and bulky. However most of the anthropomorphic hands developed to date use this type of power transmission. Some of the better known examples are now described.

2.5.1 Anthrobot Hand

A five fingered hand, the Anthrobot-2 dexterous hand was built at NASA Goddard [Vanriper et al., 1992]. It has been specifically designed for anatomical consistency with the human hand. This includes the number of fingers, the placement and motion of the thumb, the proportions of the link lengths, and the shape of the palm. The Anthrobot-2 hand has four 4-jointed fingers and a four DOF thumb. This gives a total of 20 joints in the hand, but the motion of the distal phalange of each finger is coupled to the motion of the medial phalange, giving 16 independent DOF. Both left and right hand versions have been built.

Each independent joint is connected to a servo motor via a tendon system where each tendon is enclosed in a flexible conduit. The tendon is attached to the motor via a pulley, and this causes control problems since the conduit is effectively a spring separating the controller from the joint to be controlled [Zink & Kryiakopoloulos, 1993]. Another source of problems is the large coulomb friction in the system that causes hysteresis between the joint and the servo in both position and torque. To try and get around these problems a potentiometer is used at each joint and servomotor.

The Anthrobot-2 hand has a two DOF wrist and is compact enough that the whole package, including motors, will mount on the end of a robot arm, although at 457 mm it is still reasonably long. It is currently teleoperated using master/slave control with a data glove, but autonomous control is intended at a later date.

2.5.2 Hitachi Hand

Although cable operated, the Hitachi hand [Rosheim, 1994] has a reasonably compact and very light weight power pack. The complete hand and power pack weighs 4.5 kg. Twelve shape memory alloy (SMA) metal wire actuators power the three four-jointed fingers of this 12 DOF hand (Figure 2-11). The SMA wires oppose springs, and when they are heated an electric current, they contract against the force of the spring. Upon cooling they return to their original length. Each SMA actuator is attached to a Bowden cable that runs over the back of the metacarp to the joint being actuated. The problem however is that even though the actuator system is fast and light, the SMA wires have a very low fatigue life.

The Hitachi hand is also fitted with a SMA actuated 2 DOF wrist.

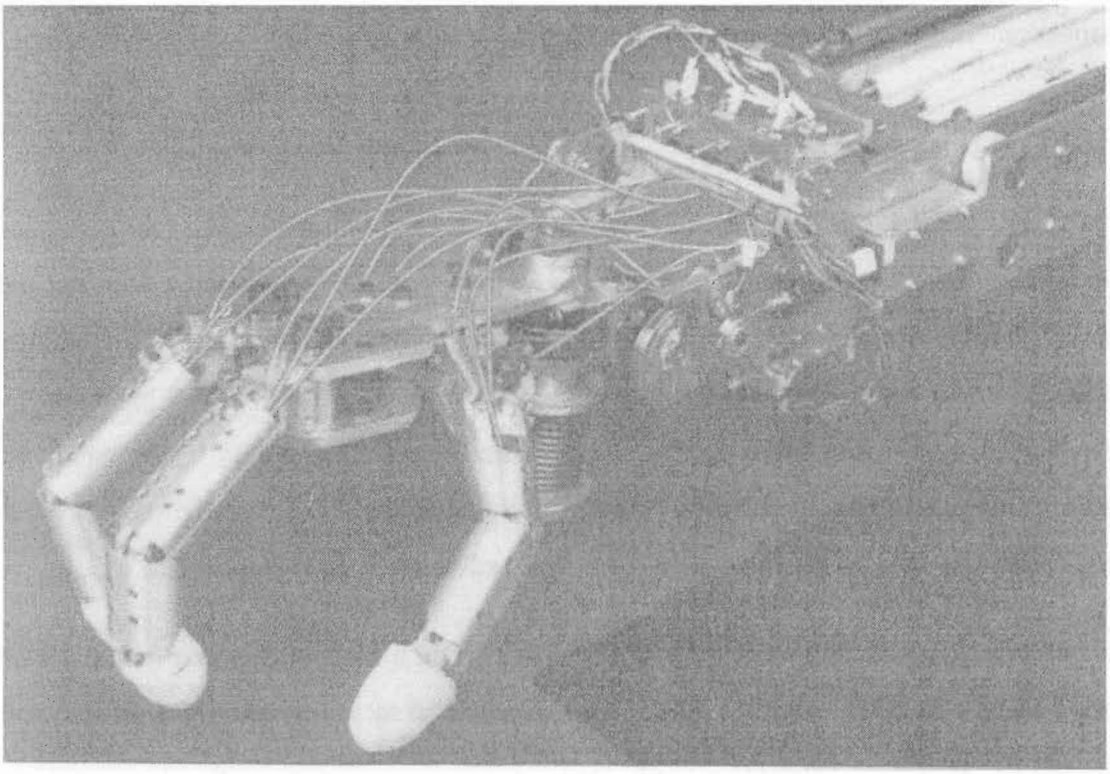


Figure 2-11 *Hitachi hand [Rosheim, 1994].*

2.5.3 Jameson Hand

The Jameson hand (Figure 2-12) is a similar tendon operated design to the well known Utah/MIT hand (Section 2.5.7, page 30) [Rosheim, 1994], but has only two fingers and one thumb. The tendons in this hand are routed through three conduits to protect them from entanglement and damage, making a more rugged and practical design than the Utah/MIT hand. However these conduits limit the range of motion of the Jameson hand's bevel gear type wrist. The wrist and finger and fingers are all driven by electric motors housed in the forearm.

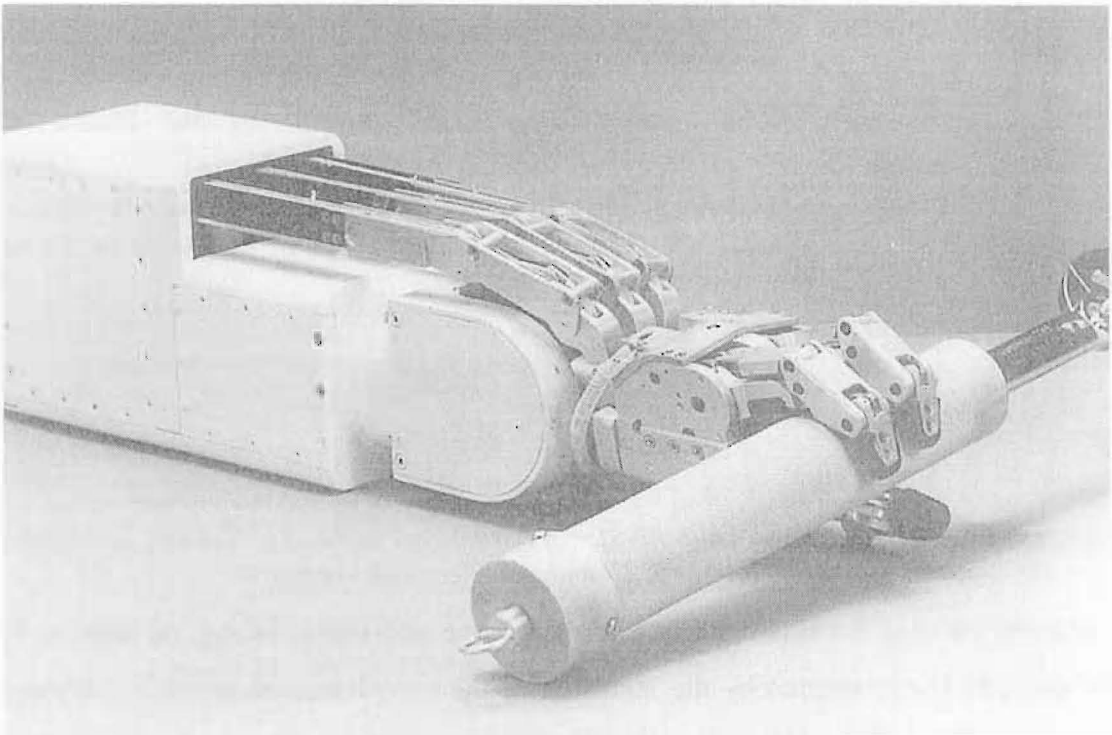


Figure 2-12 *The Jameson hand [Rosheim, 1994].*

2.5.4 JPL Hand

The JPL hand (Figure 2-13) was developed by Bruno M. Jau [1995] at the Jet Propulsion Laboratory, California Institute of Technology. It is aesthetically pleasing to look at because of its totally enclosed design with a smooth metal skin that protects the working mechanism. This hand is also an anthropomorphic cable operated hand and has three fingers and one thumb. It is equipped with a with variable compliance mechanism to control joint stiffness. This provides force control for the hand, since the force applied is directly proportional to the stiffness of the mechanism. It also allows the hand to wrap snugly around an object – i.e. the hand is not dependent on the control system to provide exactly the right grip shape since the phalanges can deflect due to the compliance in the joints. Three out of the four joints in each finger are provided with compliance (the distal interphalangeal (DIP) joint is not) using one compliance motor per finger. The hand has 16 independent DOF, not counting the compliance mechanism. A three DOF wrist is fitted between the hand and actuator pack, and also has a motor controlling joint compliance.

The JPL hand is controlled via a teleoperation system (Figure 2-13b) that uses a glove controller and provides force feedback to the operator.

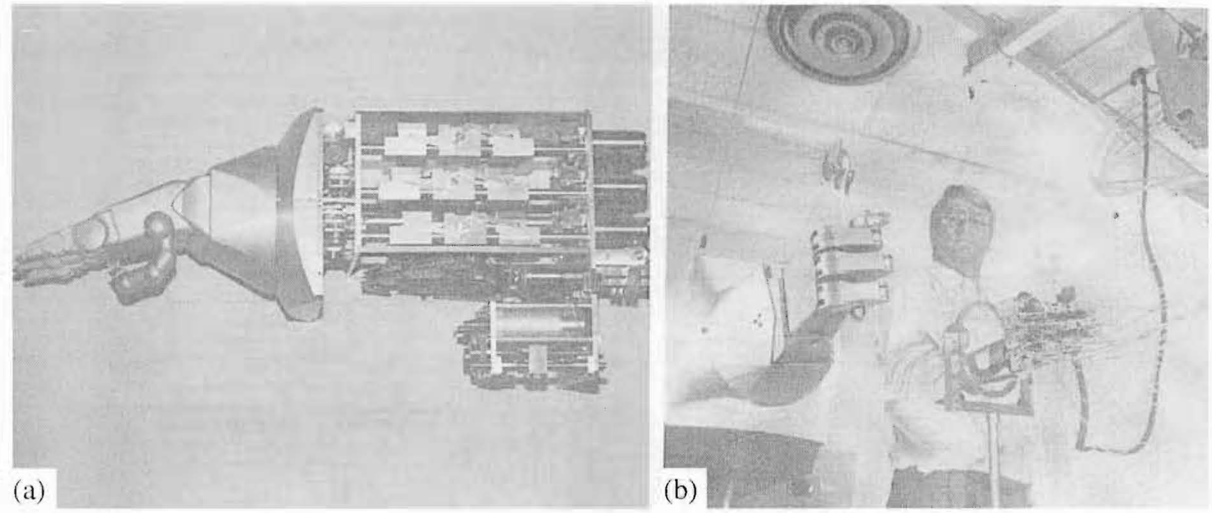


Figure 2-13 *The JPL hand [Jau, 1995]. (a) Partial view of the JPL dexterous mechanical forearm. (b) The JPL hand and telerobotic controller.*

The actuator package for this hand is extremely large and bulky, as can be seen in Figure 2-13a, and this is accentuated by the inclusion of the compliance mechanism, although the hand itself is approximately the same size as an average male human hand. It is claimed by Jau [1992] that this hand has approximately half the strength of a human hand, with 20 N normal force at the finger tip and 34 N normal force at the thumb tip.

2.5.5 Mitsubishi Heavy Industries Hand

The Mitsubishi Heavy Industries hand was designed for teleoperation in the nuclear industry [Oomichi et al., 1990]. It has already been used to disassemble 1500 lb (682 kg) check valves using conventional human tools, as can be seen in Figure 2-14. It is a 14 DOF cable operated anthropomorphic hand, and uses electric motor actuators. There are three joints per finger for each of the three fingers, and four joints in the thumb. A single joint that curls all three fingers at once is situated in place of the metacarpo phalangeal (MP) joint.

Bilateral Control (sensation feedback as well as force feedback) has been incorporated into the master/slave teleoperation system used to control this hand. Tactile stimulators in the control glove give feedback of touch sensations to the operator.

Joint sensors were used in the design since the wire cables were expected to behave non-linearly due to elasticity and to have hysteresis due to friction.

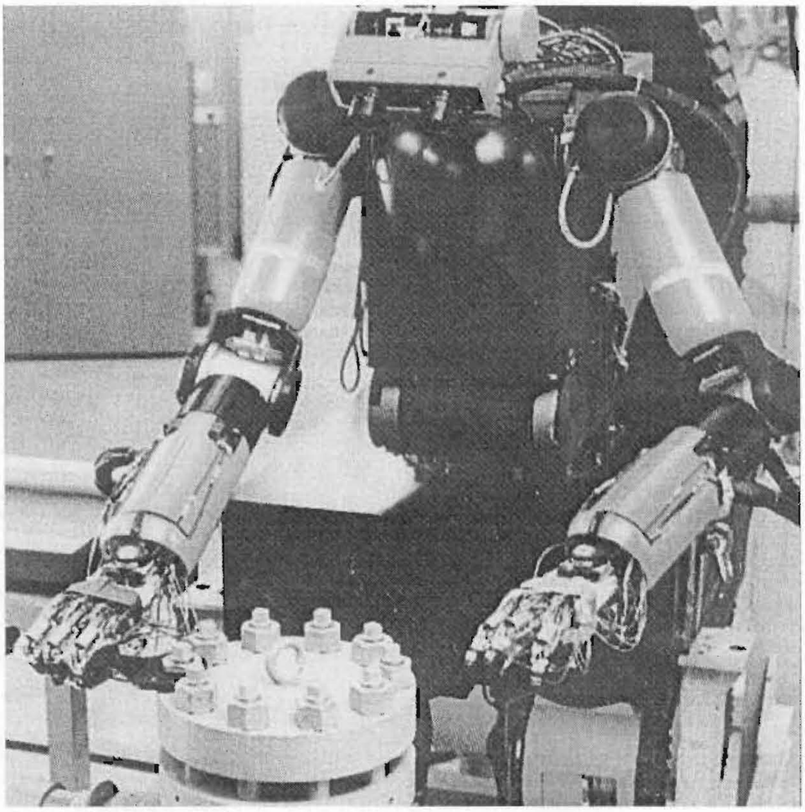


Figure 2-14 The Mitsubishi Heavy Industries hand in use.

2.5.6 Salisbury Hand

The Salisbury, or Stanford/JPL, dexterous hand was developed by Kenneth J. Salisbury at Stanford University [Salisbury, 1984]. It is composed of three identical 3-DOF fingers arranged with one finger opposing the other two, as a thumb. The finger mechanism has three joints: two parallel axis joints to provide the curling action of the finger (flexion and extension), and a third proximal joint, perpendicular to the other two axes, to provide the side-to-side motion (adduction and abduction) as shown in Figure 2-15.

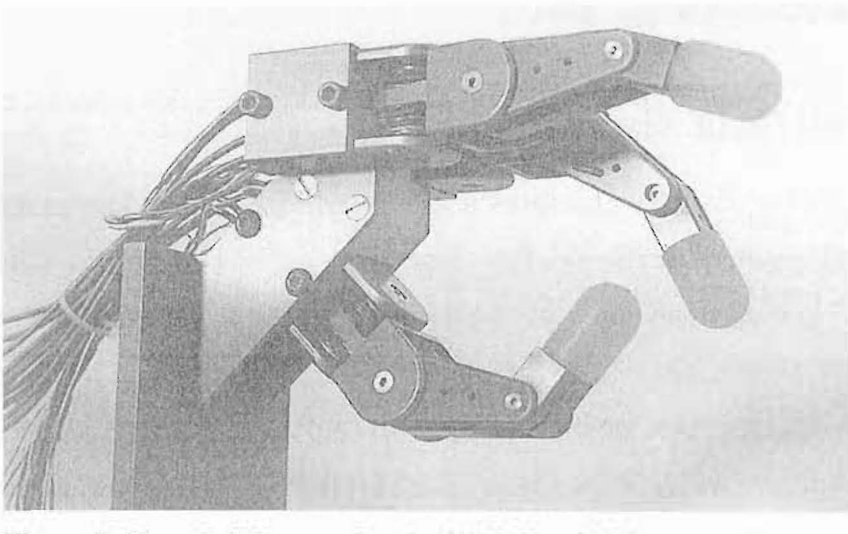


Figure 2-15 Salisbury or Stanford/JPL Hand [Murray et al., 1994]

The Salisbury hand is commercially available and has been widely used in research, partly because of its simple and reasonably robust mechanical design.

As shown in Figure 2-16 the fingers are operated by a pack of 12 electric servomotors via Bowden cables. The actuator package is reasonably large and heavy. As with other cable operated hands, the Salisbury hand suffers from high frictional losses and elasticity in the cables.

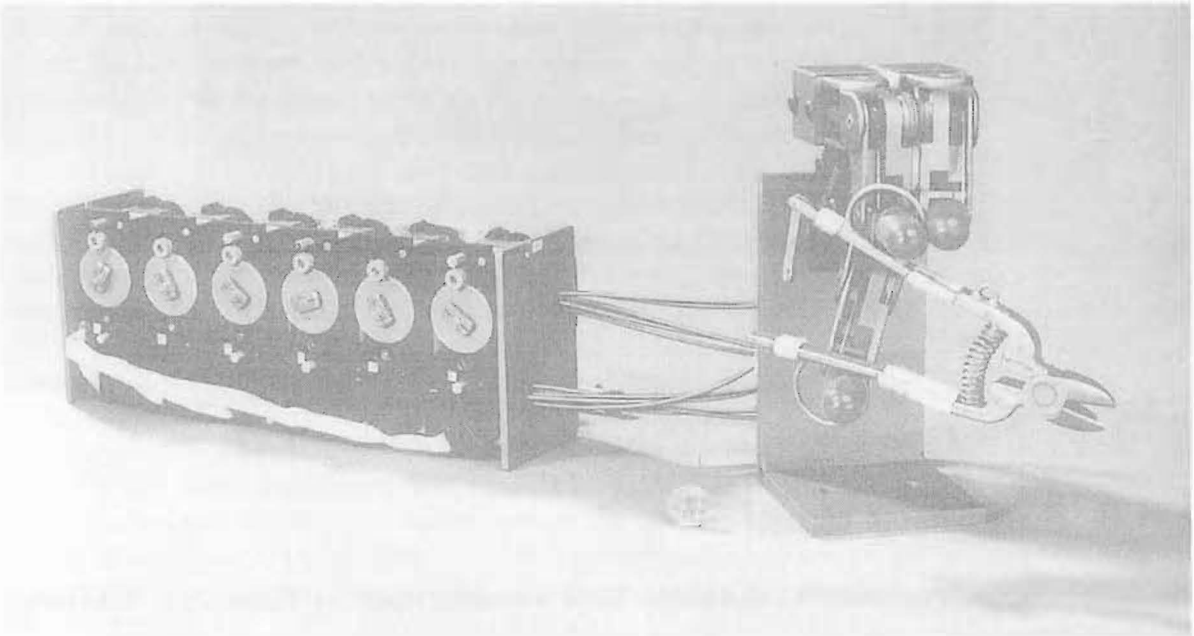


Figure 2-16 *Salisbury hand with actuator pack [Rosheim, 1994].*

Control of the Salisbury hand is also reasonably complex since each finger is controlled by four actuators, and tension sensors on each cable, which co-operate to manipulate any of the three joints, rather than having a single actuator controlling a single joint or DOF. This also makes calibration of the hand difficult to maintain [Guo et al., 1991], especially when taking into account the elasticity of the cables.

2.5.7 Utah/MIT Hand

The Utah/MIT dexterous hand [Jacobsen et al., 1986], one of the most ambitious efforts to develop an anthropomorphic robotic hand, was developed to perform laboratory research on grasping and finger manipulation. As shown in Figure 2-17, the Utah/MIT dexterous hand has three 4-DOF fingers and one 4-DOF thumb, with 32 independent tendons and actuators arranged in antagonistic pairs, yielding a total of 16 DOF. The actuators are pneumatic double acting glass cylinders running at pressures from 50 – 100 psi (345 – 690 kPa) that will produce frequencies of up to 20 Hz in the fingers. This high dynamic performance is characteristic of many cable operated systems because tendons make low mass designs possible [Rosheim, 1994]. Although tendon life cycles continue to be improved, the reliability of tendons and cables is poor in comparison to solid links. Unpredictable failures occur at the point where the flexible tendon enters the stiff clamping mechanism. The Utah/MIT hand uses a system of 288 pulleys to try and cut down frictional losses and reduce wear on the tendons. Stretching of the tendons also requires regular recalibration of the hand.

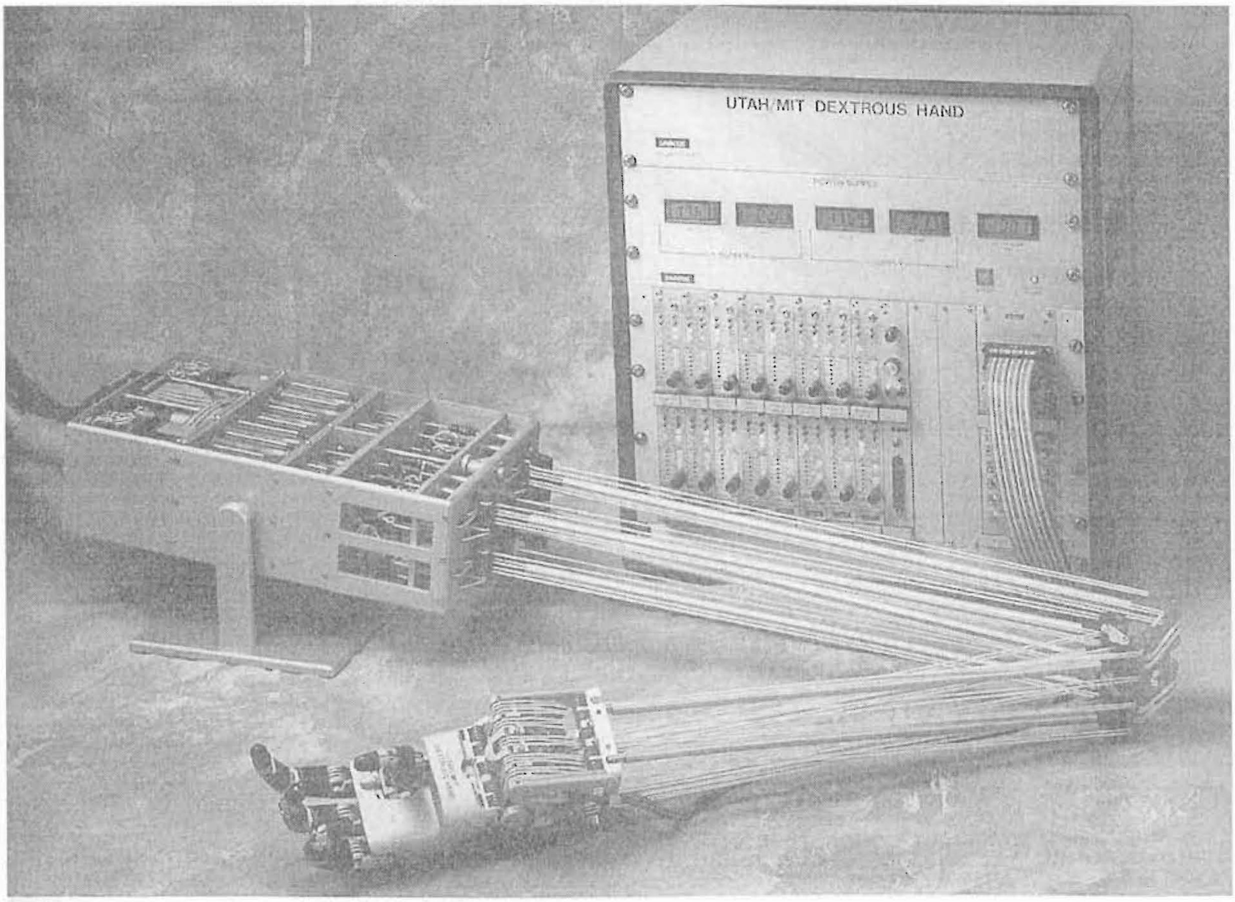


Figure 2-17 *Utah/MIT Dexterous Hand, actuator pack and controller. [Rosheim, 1994]*

Control is difficult because there are so many actuators, the tendons are compliant, and adduction and abduction of the MP joint interferes with the flexion and extension motions of the other finger joints. Small movements in the actuators for the other three joints have to be made to allow them to remain stationary while the finger is adducted or abducted. A complicated arm-like frame is also required to support the tendons while allowing the hand to move relative to the actuator pack without affecting the movement of any of the fingers.

2.5.8 Victory Enterprises Hand

The Victory Enterprises hand is an anthropomorphic hand with three fingers and a thumb. The drive arrangement is unusual in that is uses two counter-rotating lead screws that are running continuously to drive the fingers. "Actuator modules" containing high helix angle lead screw nuts connected to electromagnetic clutches run on the screws, as is shown in Figure 2-18. The direction the module is driven in depends on which clutch is activated. The actuator modules are connected to the fingers via cables. The force applied at the finger tip can be varied by controlling the current supplied to the clutch, but speed control is difficult with this method [Rosheim, 1994].

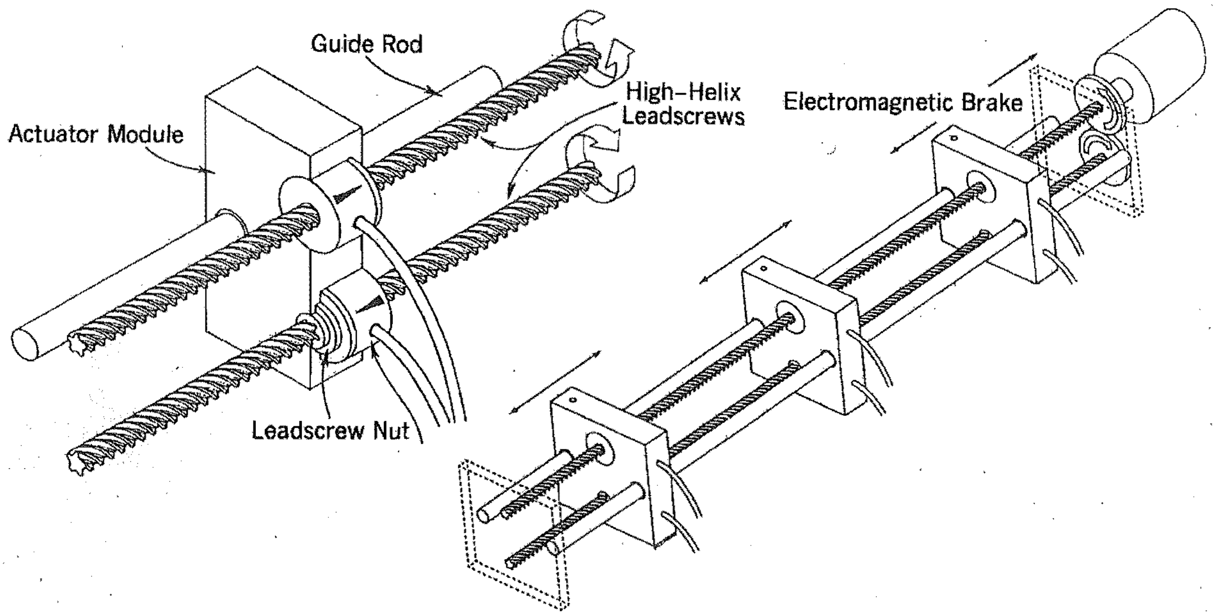


Figure 2-18 *Victory Enterprises hand actuating mechanism [Rosheim, 1994].*

2.5.9 WABOT-2 Hand

The WABOT-2 (WAseda roBOT-2) hand shown in Figure 2-19 was designed by Professor Ichiro Kato at Waseda University, Japan, to play an electronic organ. The usefulness of this cable operated hand for grasping and manipulation is very limited, but it is still an interesting example of a cable operated hand. Because the movement of the DIP joint in the human hand is largely dependent on the movement of the PIP joint, the DIP joint was omitted from this hand leaving it with four three DOF fingers and one two DOF thumb giving a total of 14 DOF.

Despite the DC servomotor actuators being located in the torso of the keyboard playing robot that the hand is attached to, the fingers can still be operated at speeds of up to 15 strikes per second on the keyboard.

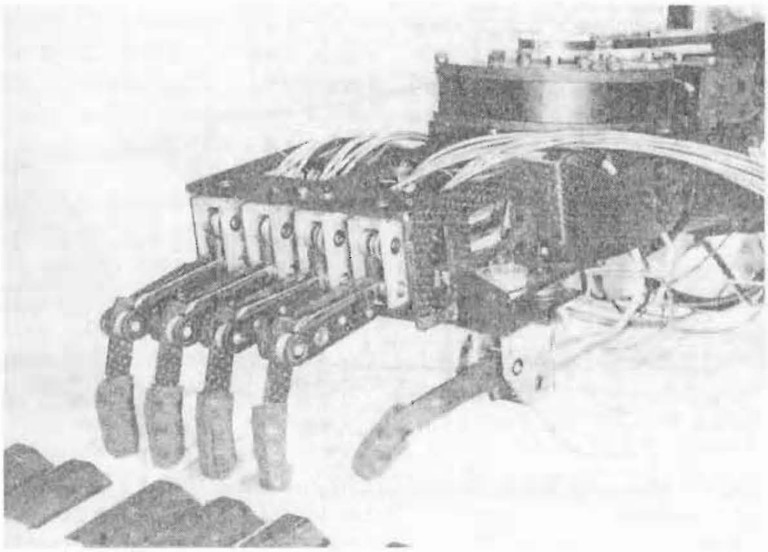


Figure 2-19 *The WABOT-2 hand poised above a keyboard [Sugano & Kato, 1987].*

2.6 Direct Driven Anthropomorphic Hands

With a direct or rigid linkage driven design, the only compliance in the hand system is deliberately added, albeit through a compliant covering to improve grip or active compliance provided through force sensors and the hand control system. Some of the existing designs do however suffer problems with backlash in the linkages. In order to keep the size of the actuator package within reasonable limits these hands tend to have fewer DOF than some of the cable or tendon operated hands. Usually there are a reduced number of digits, as with the Omni hand, or the motions of the fingers are coupled together, and/or the finger joints are coupled, as is the case with both the Belgrade/USC and Southampton hands.

2.6.1 Belgrade/USC Hand

The Belgrade/USC dexterous hand is an anthropomorphic end effector for robot manipulators. Its design (shown in Figure 2-21) is based on the Belgrade prosthetic hand [Tomovic and Boni, 1962] developed in the 1950's (Figure 2-20). The Belgrade prosthetic hand had five fingers controlled by a single motor which drove them via whiffle trees*. When any finger pad contacted the object being grasped the rest of the fingers kept moving until they too contacted the object or reached the end of their travel, and the motor kept driving until the pressure reached its desired level. This hand used carbon loaded foam pressure sensors to measure grip strength.

* See Glossary

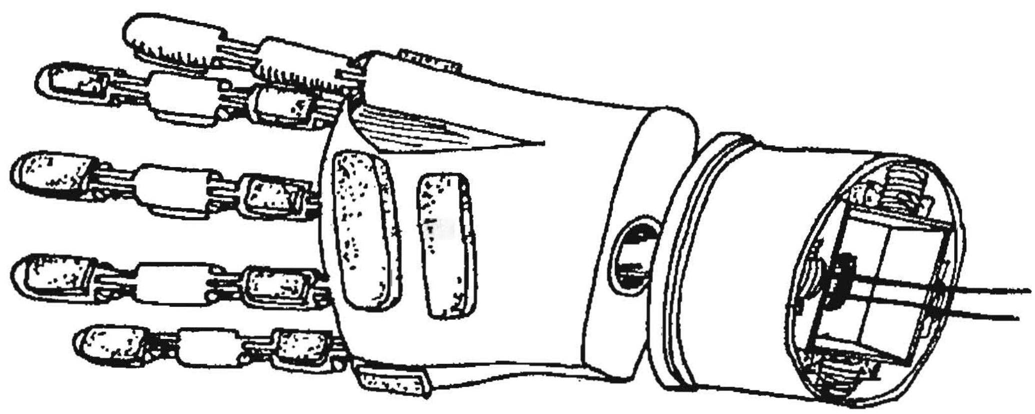


Figure 2-20 *The original Belgrade prosthetic hand [Tomovic & Boni, 1962].*

There have been 3 stages in the evolution of the Belgrade/USC hand. The model I hand has 2 DOF, and a fixed thumb [Bekey et al., 1990]. The fingers are driven through a whiffle tree, as in the original Belgrade/USC prosthetic hand, but the whiffle tree is split in two, each half driving a pair of fingers. Each whiffle tree has its own drive motor.

The model II Belgrade/USC hand [Bekey et al., 1990] adds a 2 DOF thumb to the model I hand, bring the total mobility for the hand up to 4 DOF. The thumb is driven by two DC servomotors and is able to adduct, abduct flex and extend.

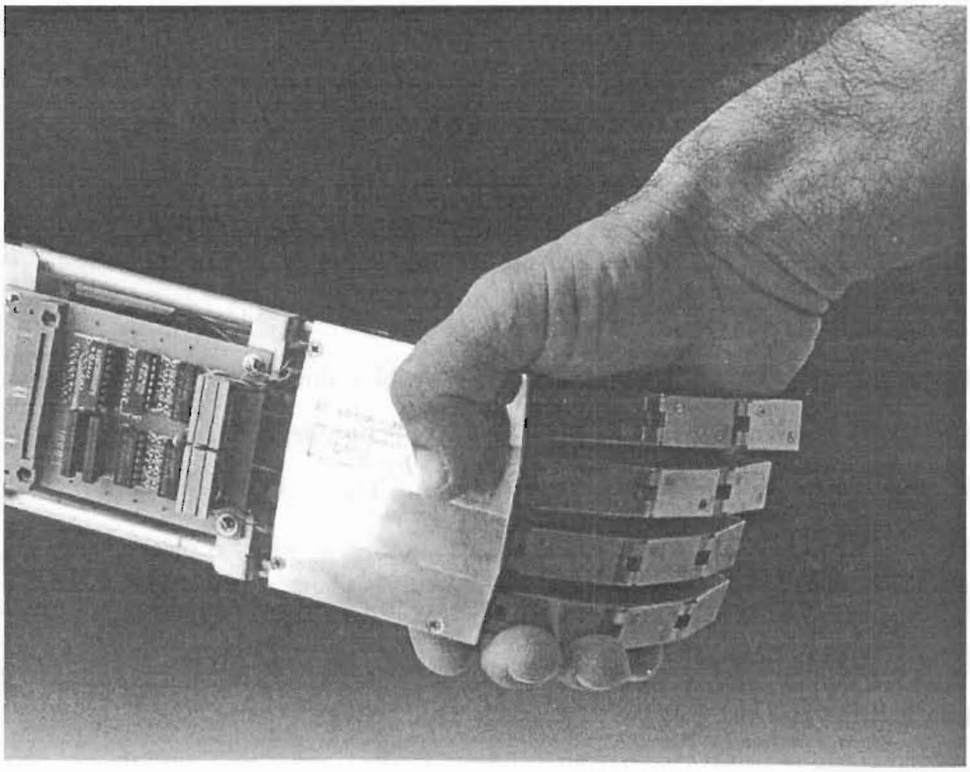


Figure 2-21 *The Belgrade/USC model II hand. A robotic manipulator [Rosheim, 1994].*

A model III hand is under development by Vuskovic at San Diego State University that will have 6 DOF, with each finger having its own drive motor.

2.6.2 Omni-Hand

The Omni-Hand [Rosheim, 1994] is an anthropomorphic hand developed by Ross-Hime Designs in the United States. It is a 9 DOF design having 2 fingers and a thumb, as shown in Figure 2-22. The actuator, called a Miniac, is a small DC motor, gearbox and screw, attached directly between the finger links.

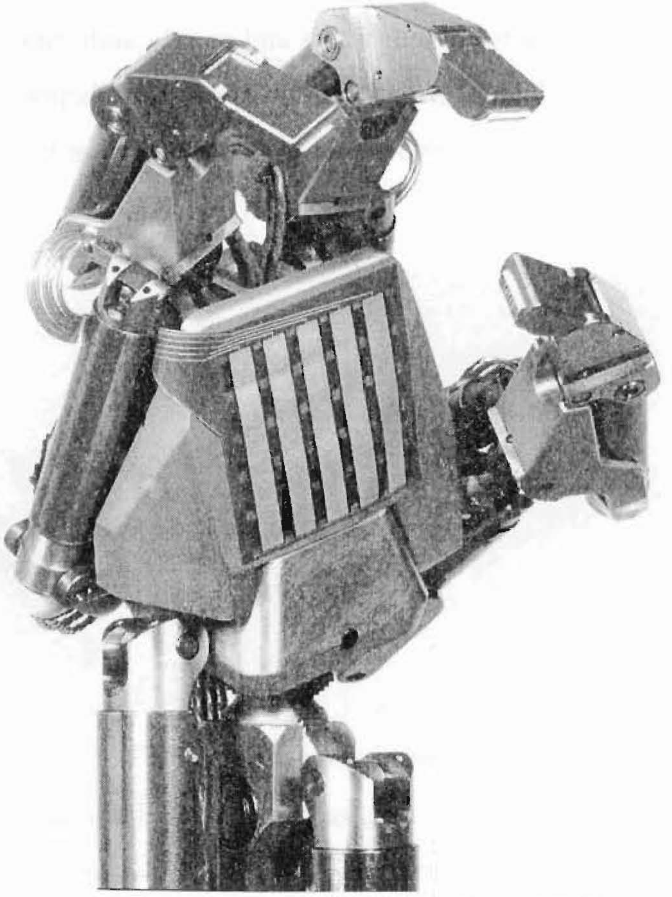


Figure 2-22 *Omni hand [Rosheim, 1994]*

Each of the digits has three independent DOF and one dependent DOF giving a total of 12 DOF. The independent DOF are pitch and yaw about the MP joint, and pitch about the PIP joint. Movement of the distal phalange about the DIP joint is dependent on the position of the medial phalange.

The design has good dexterity, is compact, and incorporates tactile sensing in the palm and finger tips. The force output is also very good, with 6 kg (59 N) available at the finger tip. The aesthetics of the design however are not great. The ends of the Miniac actuators protrude a good 30 mm from the back of the proximal link, although much of the rest of the design in quite compact. It also includes a compact two DOF wrist that uses a larger version of the Miniac finger actuator.

2.6.3 Southampton Hand

The Southampton hand, shown in Figure 2-23, is a 4 DOF hand that, unlike most of the other hands reviewed, has been designed as a prosthetic device. The first Southampton hand was a four DOF hand with adaptive control and was built at Southampton University in 1969 using discrete logic components in the controller. This used electromyographic (EMG) signals to control the hand. A realistic clinical application required the electronics to be reduced to a size and cost that is acceptable to the end users and supply authorities [Kyberd & Chappell, 1994]. Since this time the SAMS (Southampton Adaptive Manipulation Scheme) control system has been developed for the hand and the electronics have been reduced to a useable size.

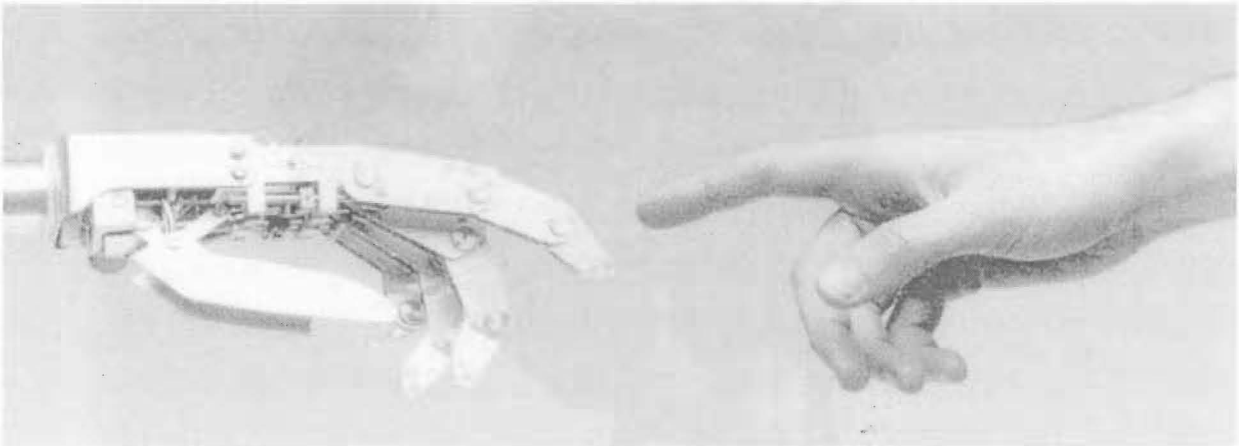


Figure 2-23 *The Southampton hand and a human hand [Chappell & Kyberd, 1991]*

The control system is easy to learn to use and sophisticated enough that a new user can be carrying out quite complex tasks within 15 minutes of having the hand fitted. Tactile sensors on the fingers and palm indicate to the controller when an object is contacted, and a slip sensor in the thumb indicates that the gripped object is slipping so that the grip force can be increased. The whole aim of the control system has been to remove as much of the low level control from the user as possible.

The digits are driven by solid links, but in this case the links are used as pull rods, being placed under tension to close the hand, as compared to the Belgrade/USC hand that uses the links as push rods. Figure 2-24 shows some of the more complex grasps possible with this hand. It produces a grip force of 120 N, which is very good.

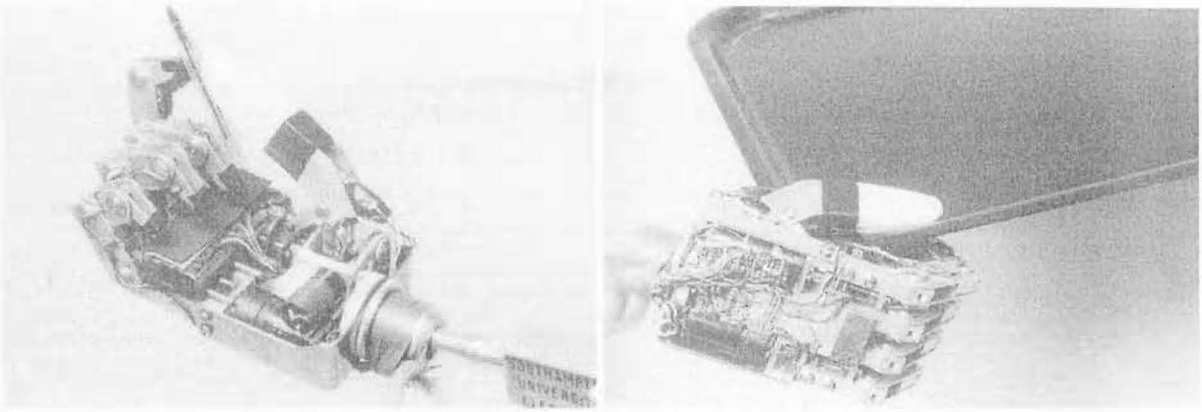


Figure 2-24 *Precision and side opposition grasps performed by the Southampton prosthetic hand [Chappell & Kyberd, 1991].*

The Southampton hand has been shown to operate as proficiently as a mechanically controlled hook, where the user has direct force feedback, and it has been used to perform a large number of everyday tasks such as buttering toast, brushing teeth, taking a cigarette from a packet, and grasping a pen and writing with it.

2.7 Conclusions

The structure and operation of the human hand has been described and its characteristics have been described in engineering terms. Some early mechanical hands are introduced, and summaries are then written on twenty different mechanical hands.

The hands that are easiest to drive and control are the linkage operated hands, but the cable operated hands tend to be faster, and have a much higher degree of dexterity. The challenge posed is to design a hand that has the dexterity of the cable operated hands while avoiding the friction and tendon compliance problems that come with cable operation.

CHAPTER 3

Improved Hand Kinematics

In this chapter the design of the Belgrade/USC hand is discussed in more detail, and it is shown how this led to the concept for a new hand, the Canterbury hand, that would overcome some of the limitations of the Belgrade/USC design. Two French students, Laurent Magnier and Hugues Monier, visiting the University of Canterbury and working for Dr G. R. Dunlop, compared these ideas with cable and gear operated systems. The original conceptual design for the new finger mechanism was found to be superior to the other designs they considered, and their work is described. The multi-link design produced by these two students provided the basis for the work carried out by the author in developing a working finger.

3.1 The Belgrade/USC Hand

The inspiration for this research project came after discussions between Dr Marko Vuskovic at San Diego State University and Dr Reg Dunlop here at Canterbury University. Dr Vuskovic described the operation of and some of the problems associated with the Belgrade/USC hand. These problems will be discussed later in this chapter, but first a short history of the development of the Belgrade/USC hand is presented.

3.1.1 The Belgrade Prosthetic Hand

The Belgrade Prosthetic Hand [Tomovic & Boni, 1962] was developed by Rajko Tomovic from the Institute "Mihajlo Pupin," Belgrade, and G. Boni from the Biotechnology Laboratory at the University of California, Los Angeles, in the 1950s. It employed a single electric motor to drive all five fingers via a whiffle tree mechanism (Figure 3-1). Each finger closed until it made contact with the object being grasped. Once all five fingers had made contact, continued operation of the motor increased the grip force until the desired threshold was reached. The differential whiffle tree mechanism used to link the fingers ensured that the force exerted by each finger was approximately equal.

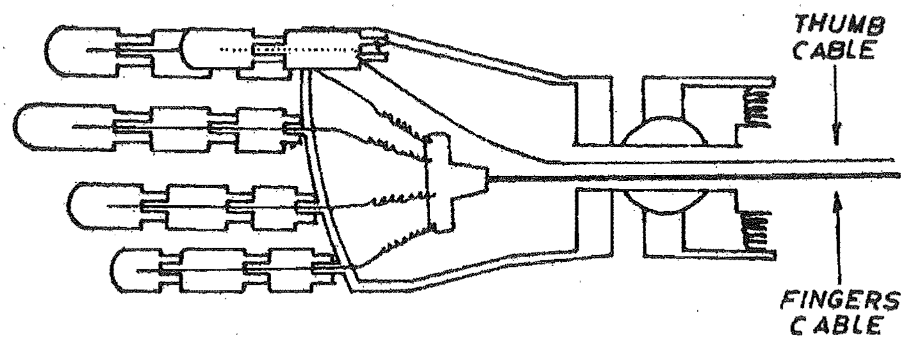


Figure 3-1 *The Belgrade prosthetic hand showing the whiffle tree arrangement [Tomovic & Boni, 1962]*

The drive mechanism was also arranged so that the operation of the thumb occurred a short time after the operation of the fingers. This was done to mimic the action of the human hand, where the thumb is used as a reference point when grasping, and does not move nearly as much as the fingers. It also allows the fingers to move past the thumb and form a fist, or a grasp rather than a pinch type grip. Rather than trying to maximise dexterity and flexibility, the hand was designed for simple control with the motions of the finger segments being co-ordinated by the built-in mechanical linkages. Each finger is spring loaded to ensure that the hand can return to the fully opened position. Thus the emphasis was on simplicity rather than individual joint control as characterised by the tendon and cable operated hands.

3.1.2 The Belgrade/USC Hand

The model I Belgrade/USC robotic hand was the first attempt by Bekey, Tomovic and Zeljkovic [1990] to apply the automatic shape adaptability and extreme control simplicity of the Belgrade prosthetic hand to an anthropomorphic end-effector for robotic manipulators. It retained the whiffle tree mechanism, but now had two motors, each driving a pair of fingers, instead of one motor driving all four. In this form it only had a rigid thumb.

The model II hand (Figure 3-2) used four electric motors to give improved dexterity. The extra two motors being used to drive a thumb that could be adducted, abducted, flexed and extended. A further development by Vuskovic et al. [1995], the model III Belgrade/USC hand, incorporated two more electric motors so that each finger could be driven independently.

The emphasis over the past decade has mainly been on software control of the hand, grasp synthesis and pre-shape, and latterly EMG control with a view to developing a new prosthetic hand based on the Belgrade/USC hand.

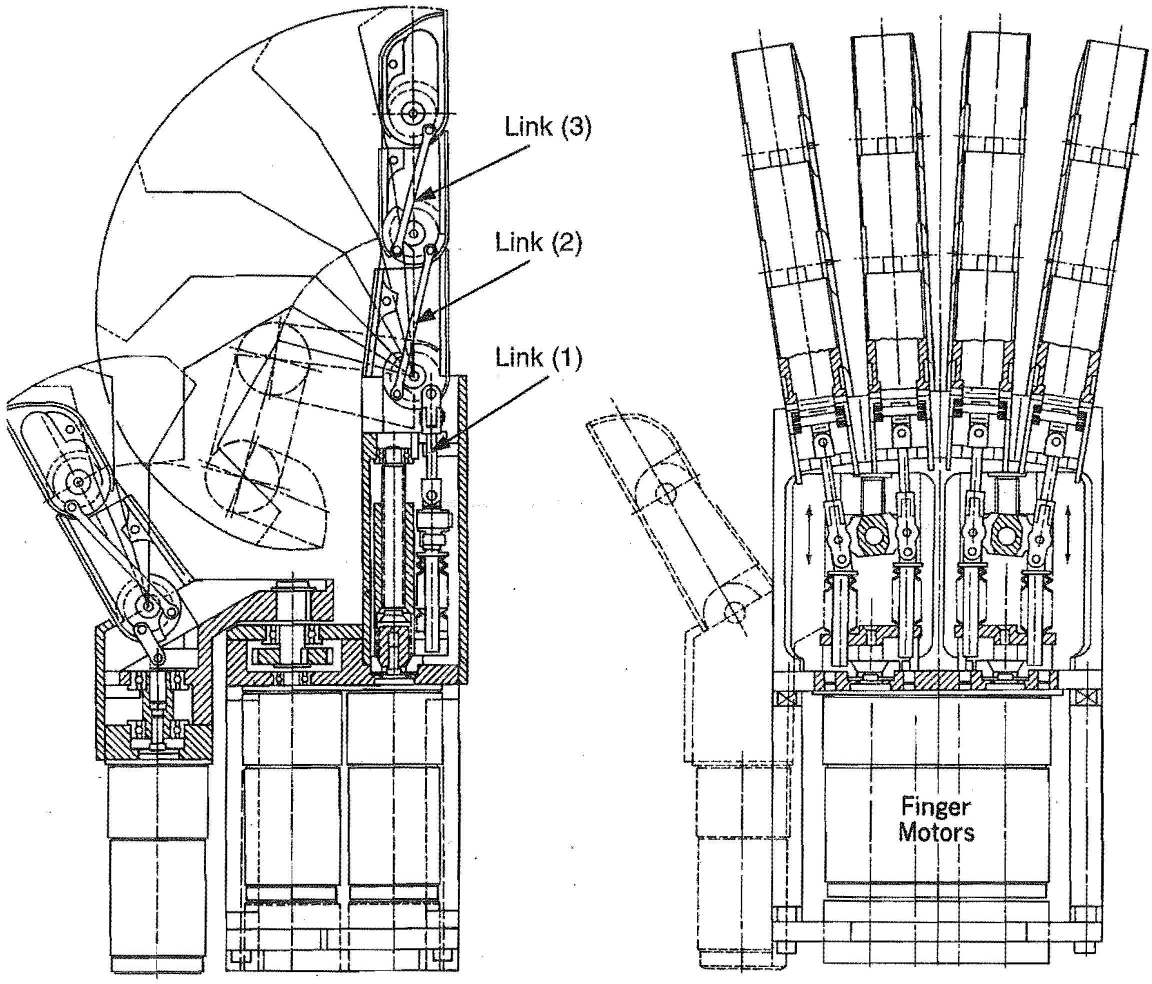


Figure 3-2 *Cross sections of the model II Belgrade/USC hand showing the operation of the fingers and thumb [Rosheim, 1994].*

The design of a finger from the Belgrade/USC hand is reproduced in Figure 3-3. The lead screw carries a nut and is driven by a DC motor. As it rotates it drives the nut in the direction indicated by the arrow. As the nut moves it pushes on the proximal link via the first link, causing the proximal link to rotate about the MP joint. As the proximal phalange rotates, link (2), which has its proximal end attached to the body of the hand, causes the medial phalange of the finger to curl also. Similarly link (3), which is attached to the proximal phalange at its proximal end, causes the distal phalange to curl also.

3.1.3 Geometry Improvements

The Belgrade/USC hand suffers from some problems with friction, backlash, and two design details in particular. One of the design detail problems is that the finger is driven by a nut on a lead screw, and the driving link is attached to the nut by a two axis joint on its top surface. When the finger was loaded the force, **F** (Figure 3-3), in link (1), generated a moment on the nut which is perpendicular to the lead screw axis. When the finger applied maximum force on a surface, this moment was often sufficient to jam the nut on the lead screw, and the finger could not be straightened. It was proposed that for the fingers of the Canterbury hand that the proximal link be driven by two links positioned either side of the nut, in line with the axis of the lead screw to remove the jamming action. These links were also to be placed under tension when exerting maximum grip forces (as in the Southampton hand) so they could be of lighter construction.

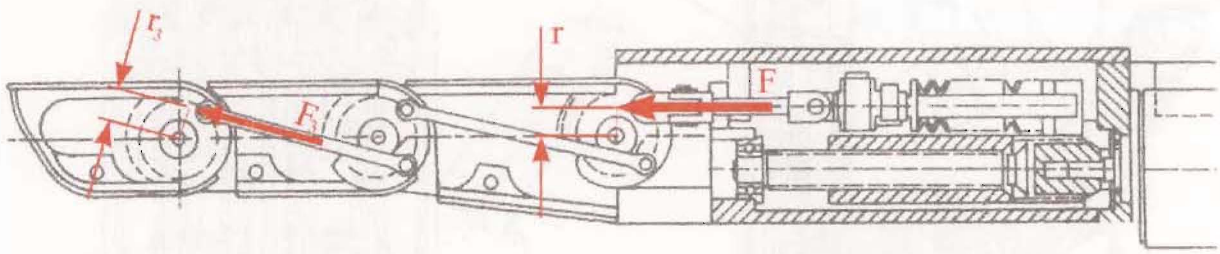


Figure 3-3 *Cross section of Belgrade/USC finger showing small working radius, and offset loading on drive nut.*

The second design detail is common in many of the mechanical hands and is as follows. The distance, **r**, between the first link attachment point on the proximal link and the MP joint (the point on the hand body about which the proximal link pivots) is less than half the thickness of the finger (Figure 3-3). For the Canterbury finger it was proposed to move the pivot of the proximal link to increase this distance, **r**. Increasing the leverage ($\mathbf{r}_2$) on the medial phalange and ($\mathbf{r}_3$) on the distal phalange has a cascade effect along the linkage train so that the force in the MP joint is reduced even further for the same finger tip force. By reducing the forces in the joints, the frictional losses in the joints are also reduced allowing smaller, lighter bearings to be used. Similarly, for the same finger tip force, the link forces are reduced enabling lighter components to be used.

These ideas provided a starting point for the design of the Canterbury hand.

3.2 Initial Concept for the Canterbury Hand

From the study of the Belgrade/USC hand, the concept for a new hand, the Canterbury hand, was developed with the following features :

- *At least 2 DOF per finger.*
- *Up to 6 fingers.*
- *Linkage operated fingers (similar to the Belgrade/USC hand)*
- *Full depth lever arms to operate each phalange.*
- *A direct pull on the finger drive nut to prevent locking.*

Laurent Magnier and Hugues Monier, two students from the Mechanical Engineering Department at Ecole Nationale D'Ingenieurs, Saint-Etienne, France, working at the University of Canterbury for Dr G. R. Dunlop, studied these ideas and compared them with cable and gear operated systems. The original concept for the new finger mechanism was found to be superior, since it avoided the compliance and frictional problems associated with cable driven designs, and the complex manufacture and backlash problems associated with gear driven designs. The multi-link design examined by these two students [Monier & Magnier, 1993] provided the basis for the work carried out by the author in developing a working finger.

This initial concept consists of a two degree of freedom mechanism operating in one plane and operated by a linkage mechanism as shown in Figure 3-4.

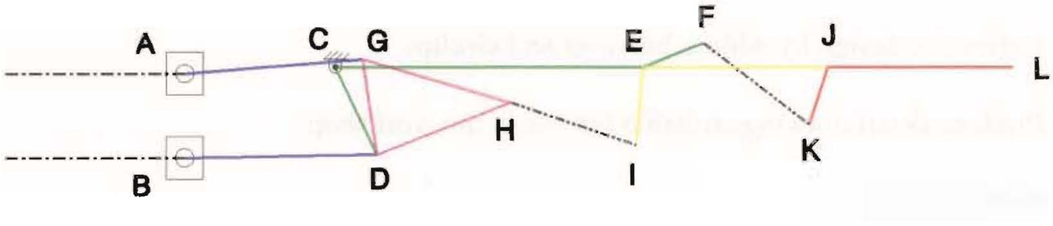


Figure 3-4 *Schematic of the Canterbury finger geometry [Monier & Magnier, 1993].*

The proximal link is driven via a four bar linkage. The medial and distal links are kinematically coupled and are driven via a five bar linkage. Each degree of freedom is controlled by a DC servomotor. These motors are each fitted with a 16:1 reduction gearbox and a ten-pulse-per-revolution quadrature encoder, giving 640 steps/revolution of the gearbox

At the end of their time at Canterbury University Magnier and Monier had defined the basic layout and dimensions of a finger. They had produced a model of a finger using the Computer Aided Design (CAD) package, MicroStation [Bentley Systems, Inc.] but the drawings produced were not suitable for use as working drawings for the workshop, and there was still a lot more detail design work to be done. A kinematic analysis had not been carried out on their final design, and the working area of the finger tip had only been calculated for an earlier evolution of their design.

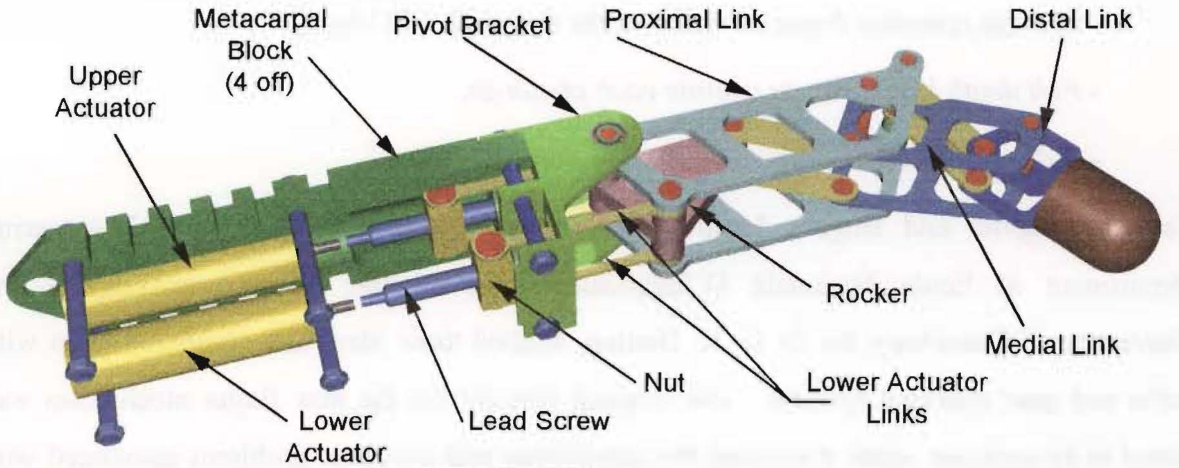


Figure 3-5 *Picture of an assembled finger generated from the CAD model produced by Monier and Magnier [1993]. Three of the metacarpal blocks have been removed to show the actuating motors and screws.*

The following tasks were proposed for the development of the finger :

- Formulate a kinematic model of the finger, and calculate its working region.
- Perform a motor comparison, and calculate the performance characteristics of the finger, including tip force and speed.
- Calculate the loads in the finger.
- Refine the design by adding bearings and circlips.
- Produce detail drawings suitable for use in the workshop.
- Build a finger.
- Test the finger and compare the results with the calculated performance values.
- Write control software for the finger.

3.3 Geometry cf the Canterbury Finger

Each finger on the Canterbury hand is driven by two electric actuators. Each of these consists of a DC motor, a 16:1 reduction gearbox and a quadrature shaft position encoder, driving a lead screw and nut (Figure 3-5). The lower actuator drives the proximal link in exactly the same way as the Belgrade/USC hand is driven, i.e. through a 4 bar linkage system. The difference in this case is that the driving link is under tension when the finger is being flexed, and in compression when it is being extended. The Belgrade/USC hand is exactly opposite to this.

The second, upper, actuator pulls the upper pair of actuator links which rotate the rocker plate. The rocker plate is pivoted on the attachment point between the proximal link and its actuator link, i.e. the rocker plate pivot is positioned by the first (lower) actuator, and the second (upper) actuator pivots the rocker about this point. The rocker plate is attached at a third point to a pair of parallel driving links which move the medial link. The geometry has been set to minimise the effect the lower actuator on the medial link. The movement of the proximal link through its 50° range results in only 3.3° of movement in the medial link. While the movements are not completely decoupled, the coupling is quite small. The distal link is coupled to the medial link so that it curls with it in the same way that the Belgrade/USC finger operates. Thus the coupling is only 6.4° in the distal link.

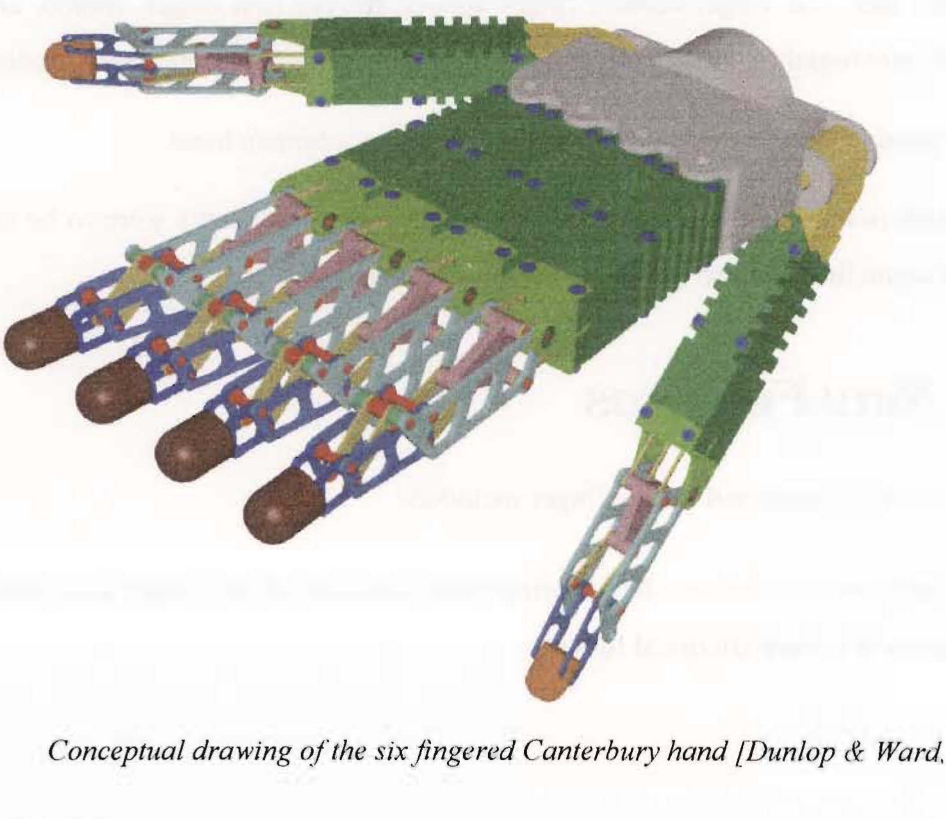


Figure 3-6 *Conceptual drawing of the six fingered Canterbury hand [Dunlop & Ward, 1995]*

3.4 Constraints

Based on the work carried out by Monier and Magnier, and the proposed purpose of the hand, a number of constraints were placed on the design, these being :

- The finger must be able to be assembled into a complete hand
- The hand, when assembled, should have spreadable fingers
- The finger dimensions should as closely as possible resemble those of a human finger. The maximum for these was taken from Magnier and Monier's work to be width : 22 mm; height : 28 mm; length : 110 mm.

The hand was not initially intended for any specific application. It could be used as a robot manipulator, or as a human prosthesis. As work progressed however it was seen that due to its small size, and relatively low power when compared to an industrial robot, that this particular implementation of the finger would be best suited to a prosthetic device. Thus the following constraints were also applied :

- The drive mechanism for the finger should be maintained wholly forward of the wrist.
- Hand (and finger) mass should be kept to a minimum.
- Control should be largely autonomous, with only a few control signals required from the user. i.e. finger adduct, finger abduct, for the first finger, thumb, and next three fingers together, along with finger spread, and thumb flexion and extension.
- Speed of operation should approximate that of a human hand.

It should be noted that readily available materials and components were to be used, and this provided some limitation to the development of the design.

3.5 New Features

The new features proposed for the finger included :

- Deep groove miniature ball bearings were added to all the finger side plate and linkage joints to reduce frictional losses.

- The finger and linkage joint pins and shafts were redesigned to carry the ball bearings. Circlip grooves were added, and spacers were designed to hold the links in their correct positions.
- A flexible coupling was designed and fitted between the motor output shaft and the drive screw.
- A radial support bearing, was added to the motor end of the drive screw and the thrust bearing arrangement was redesigned to accommodate a thrust bearing assembly rather than a single ball.
- Retaining pins were added to the drive nut to stop the drive link pins moving.

3.6 Conclusions

The Belgrade/USC hand, while overcoming the frictional and compliance disadvantages of cable operated hands, had two particular areas where the hand geometry could be altered to improve its performance. In developing the concept for the Canterbury hand, a design was chosen which prevented the drive nut locking onto the screw when the finger is loaded, and in which the frictional losses in the finger linkage mechanism were reduced to get a higher finger tip force output for a given motor torque. Lower joint forces also allowed the use of smaller lighter bearings and lighter links. The conceptual design for the Canterbury finger was evaluated by Hugues Monier and Laurent Magnier when they worked at the University of Canterbury on their undergraduate project, and from this a plan for the development of this design into a working finger was formulated.

CHAPTER 4

Detailed Development

Preliminary work on four and five bar linkages provided a good basis for the development of a new hand that would overcome many of the limitations of the Belgrade/USC hand, as discussed in chapter three. This chapter describes how the preliminary work was developed to provide a workable design for a new two DOF robotic finger. The component selection process is described, as are the important details of the design. The machining and production methods necessary to produce the finger are covered, and the finger control system that was used to test the first prototype is described.

4.1 Calculated Kinematics

An equation for the position of the finger tip as a function of motor shaft position (the forward solution for position) was developed using Mathematica® [Wolfram Research, Inc.] and MATLAB™ [The MathWorks, Inc.]. The position of each joint was found using intersecting circles for a range of motor shaft positions, and the finger tip position was plotted (Figure 4-2). This was verified using the parametric modelling feature of MicroStation® [Bentley Systems, Inc.]. The following sections describe how this was achieved.

4.1.1 The Problem

It was necessary to calculate the position of the finger tip and angles of the links of the finger as a function of the lead screw rotation or the nut movement. This information was required for the control of the finger, and to calculate the forces in the links and joints. The solution for the lower screw was reasonably trivial, since it drives the proximal link via a simple four bar linkage. The top screw, however, drives the rocker as part of the five bar linkage, and an analytical solution for this is much more difficult to formulate.

4.1.2 Co-ordinate Transforms

It was noted that the positions of the joints could be located using intersecting circles. The calculation of the co-ordinate transforms for a finger from the Canterbury hand is described in this section.

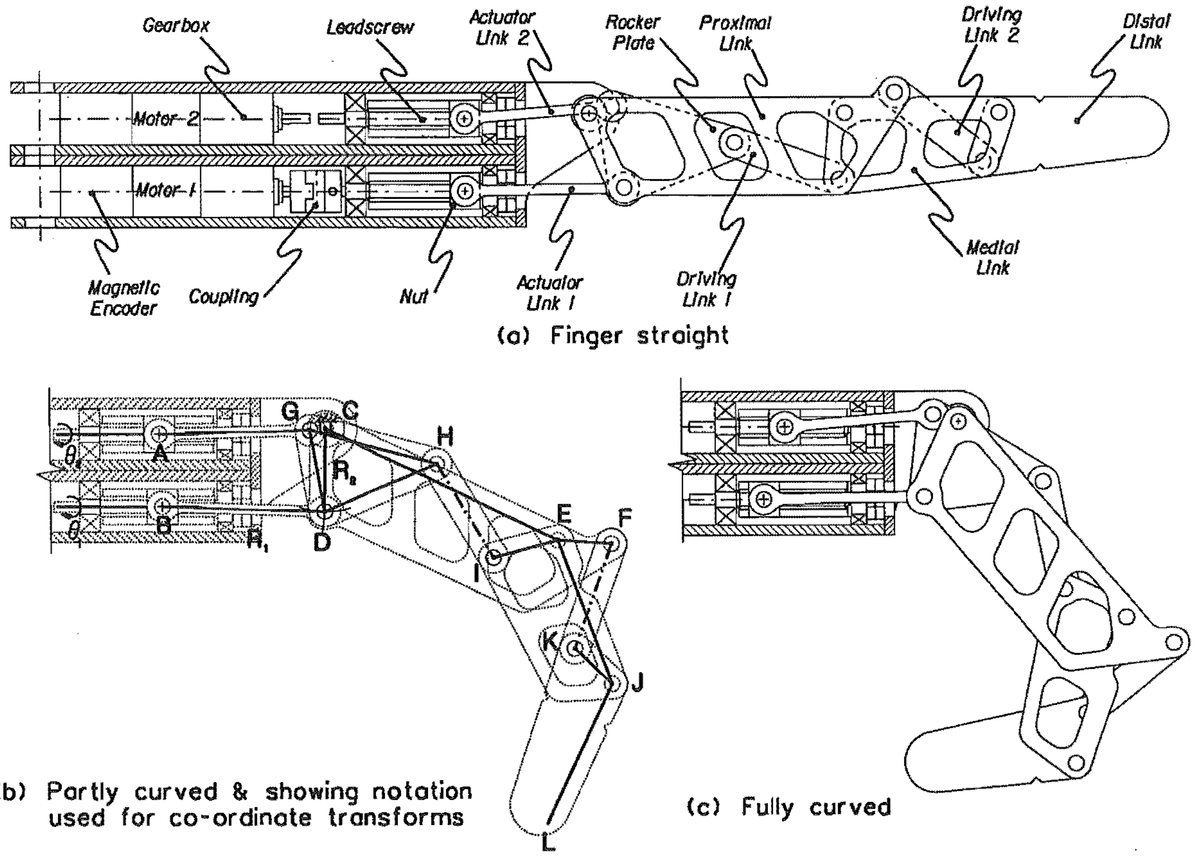


Figure 4-1 *A finger shown in the straight, half curled, and fully curled positions. The geometry and positions of the critical points used to determine the finger tip position from the motor rotations is shown overlaying the half curled finger [Dunlop & Ward, 1995].*

Mapping the rotation of the output shaft of the lower motor (motor 1) to the position of the proximal link of the finger involves calculating the geometry of a four bar linkage. Referring to Figure 4-1b, when the nut on the lower screw is positioned by rotation of the motor, the co-ordinates of the nut **B** are determined. Since the main pivot point position **C** for the proximal link is fixed and known, then the intersection of a circle of radius R_1, the length of actuator link 1, centred on **B** with a circle of radius R_2, centred on **C** yields the pivot point **D** on the proximal link and the rocker plate. Since the angle of line **CD** is known, the position of point **E** (at the end of the proximal link, and also the pivot point for the medial link) and the point **F** (the anchor point for driving link 2) on the proximal spur can be determined. Thus the pivot points **D**, **E**, and **F** are readily determined from the shaft rotation θ_1 of motor 1.

Computation of the position of the medial link involves solving the geometric problems associated with a five bar linkage. Relating the second (top) motor rotation θ_2 to the position of the second nut **A** is straight forward. Since the pivot point position **D** of the rocker plate is already determined from θ_1, the point **G** on the rocker plate can also be calculated as being at the intersection of the circles centred on **A** and **D**. Since the position of **H** on the rocker plate is fixed relative to **D** and **G**, its position is easily found once **D** and **G** are determined. The circles centred on **H** and **E** intersect at the medial link point **I**. The angle of the line **EI** allows the pivot point **J** at the end of the medial link and at the start of the distal link to be determined. Intersection of the circles centres on **F** and **J** determine the position of **K**. The position **L** at the end of the distal link is determined from the angle of the line **JK**. Thus the finger tip position is calculated from the rotations θ_1 and θ_2 of the motors.

4.1.3 The Solution

Mathematica® was used to simultaneously solve the equations of two arbitrary planar circles, and thus produce the formulae for the positions of the two possible intersection points. This formula was edited to convert it into a format suitable for use in MATLAB™. A MATLAB™ program was written to calculate the positions of the finger tip as the nuts were moved along the screws. A plot of the area swept by the finger tip is shown in Figure 4-2. Appendix D (page 105) contains a description and a full listing of the MATLAB™ program modules that were written.

This program has subsequently been used as part of a Genetic Algorithm optimisation program that has been developed by Bain [1996] to optimise the finger design.

The analysis of the working range of the Canterbury finger carried out using MATLAB™ indicated that a singularity occurs in the mechanism, as indicated in Figure 4-2. Beyond this point MATLAB™ gave imaginary values for the finger tip position indicating that the function describing the finger was no longer analytic. Further analysis showed that this singularity existed along a curve stretching to the left of this first singular point. However by limiting the travel of the top drive nut to 9.38 mm (8580 encoder counts) none of the other singular points were ever reached. Although this reduces the working area of the finger tip slightly, it greatly simplifies finger control.

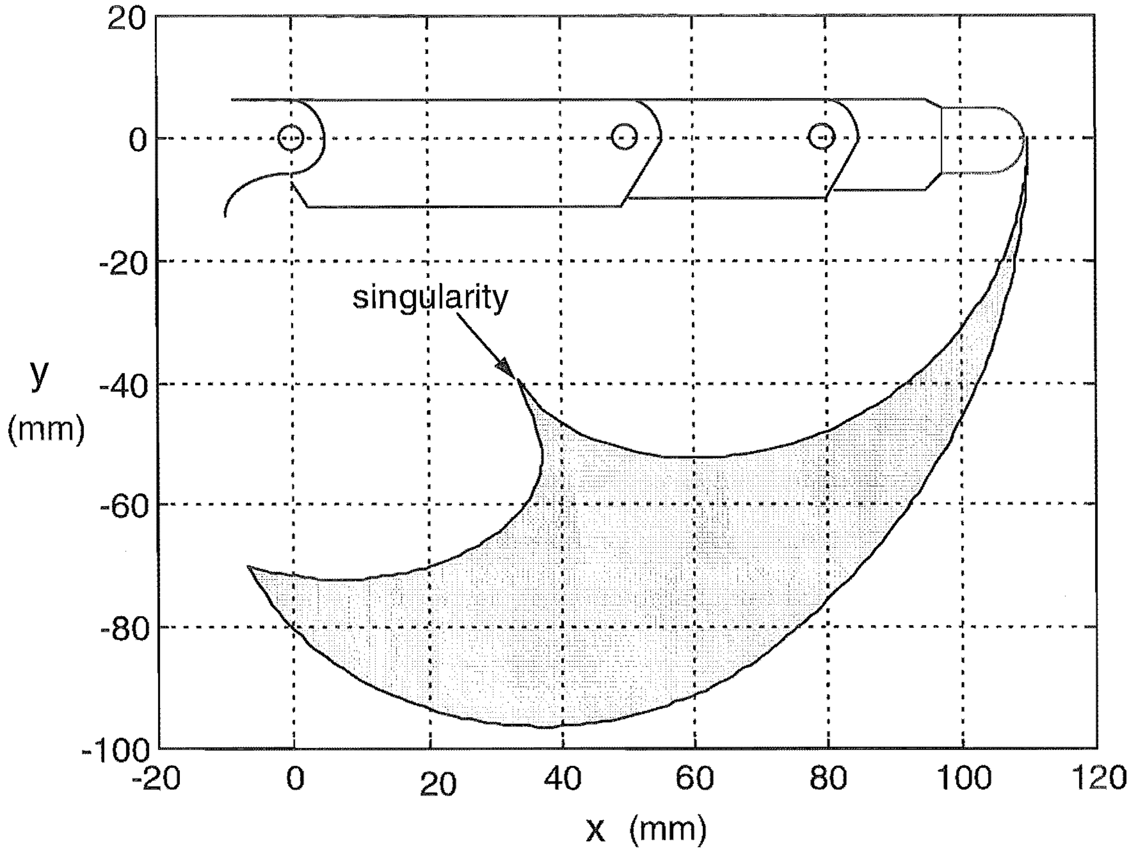


Figure 4-2 *Working range of the finger tip calculated using MATLAB™*

4.1.4 Checking Geometry, Working Range, and Positions of Singularities

A parametric model of the finger was developed using the parametric modelling feature of MicroStation®. By manipulating the model the movement of the finger segments could be observed. The finger was moved through its full range, subject to the lead screw length and mechanical interference constraints, and the work space of the finger tip was plotted. The position of a singularity predicted by MATLAB™ was confirmed, and is clearly shown in Figure 4-3. Both simulations agreed that the first singular point was reached when the upper nut had been moved 9.38 mm from the nut's zero position and the lower nut had not been moved from this zero position (Figure 4-3). Because of the coupling between the two degrees of freedom, the position of the upper nut when the singular point is reached depends on the position of the lower nut.

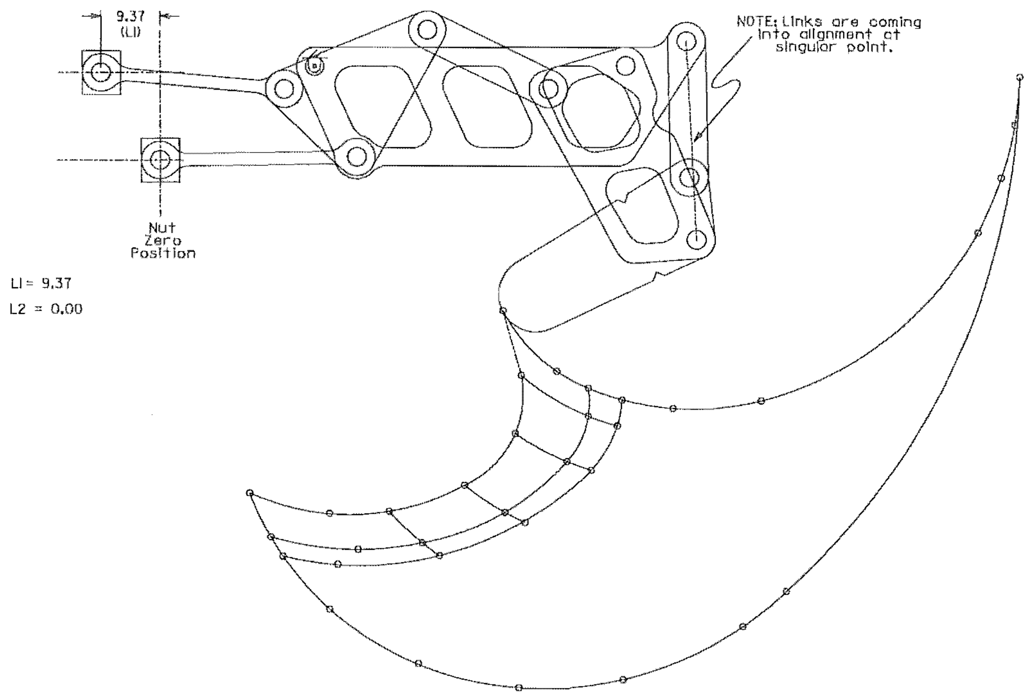


Figure 4-3 *Parametric model of the Canterbury finger generated in MicroStation®, showing the workspace of the finger tip, and the singular point in the workspace.*

The parametric model of the finger was also used to evaluate designs produced by Bain [1996] using his Genetic Algorithm optimisation programs. The link lengths in this parametric model can be changed by editing a table containing the values of all the finger parameters, and then the model can be manipulated to flex and extend the finger by changing the parameter that denotes the position of the nut on the drive screw. This very quickly gives an indication of the working region of the finger tip and the position of any possible singular points.

4.2 Component Selection

Even though two motors had been chosen to drive the finger proposed by Magnier and Monier, only a rough evaluation of their suitability had been made. Thus it was decided to make a comparison of the packages available. Then, with an idea of some of the loads on the finger, the selection process for the other major bought-in components required could be carried out. Bearings needed to be selected for the finger joints, and for mounting the lead screws. A survey of the types of lead screws available was also carried out.

4.2.1 Motors

An alternative supplier of miniature DC motors, and a supplier for very small brushless DC motors were found after the first two motors had been ordered. Consequently a comparison of the available drive packages available was carried out, the full details of which can be found in Appendix B, page 91.

Table 4.1 *Summary of motor dimensions and performance.*

MOTOR	DIAMETER	LENGTH	WEIGHT	SPEED - FOR FULL TRAVEL	TIP FORCE
Maxon RE-013-35-10EAB103A	13 mm	68.1 mm	40.25 g	1.45 s	61.9 N
Transicoil 05LH24*	12.5 mm	50.8 mm*	35 g*	0.19 s	335.3 N
Minimotor 1016 M 006 G	10 mm	41 mm	18.5 g	1.05 s	5.4 N

The Maxon RE-013-35-10EAB103A motor [Interelectric AG, 1994] gave much better performance - over eleven times the force (61.9 N) exerted at the finger tip, compared with the Minimotor 1016 M 006 G motor [Minimotor SA, 1992] (5.4 N). However due to its greater external dimensions (13 mm diameter, 68.1 mm long) it was decided that the 10 mm diameter, 41 mm long Minimotor motor would be more suitable for a prosthetic hand. The lower power consumption and weight of the Minimotor motor also make it more attractive for a prosthetic device, and the calculated grip force still reaches 10 N, the level required for 80% of grasps [Kyberd, 1995]. This grip force is achieved using two fingers to oppose a thumb running with a higher gear ratio, and hence with twice the tip force, but at half the speed. Running the thumb slower mimics the human situation where the thumb is often used as a reference point when grasping and is not moved nearly as much as the other fingers. For a finger designed for purely robotic it is proposed to use the use the larger Maxon motors.

The Transicoil motor [Transicoil Inc., 1996] looks very attractive, but the problem was obtaining a suitable speed reducer. The maximum no load speed was 100,000 rpm compared with approximately 16,000 rpm for the other two motors. The Transicoil also draws a very high current at stall (where this high torque is generated) — 28 A (at 24 V DC). This would be difficult to supply to a robotic hand, requiring 15 rather large drives for a six fingered hand, and it is not feasible to try and supply this kind of current (15×24 A or 420 A) to a prosthetic

* Weight and length are quoted without a gearbox, but the tip force is calculated using a 16:1 reduction gearbox, assuming that a suitable gearbox could be obtained.

hand. The operating temperature of this motor when delivering such a high torque is also very high. Approximately 100° C, even with a $100 \times 100 \times 12.5$ mm heat sink. This would cause some major cooling problems for a hand with so many motors in such close proximity.

4.2.2 Bearings

Rolling element bearings were chosen for use throughout the finger so as to keep frictional losses to a minimum. Deep groove radial ball bearings were chosen for use in the phalanges, and to support the drive screw, and a thrust bearing unit was incorporated to carry the end load on the lead screws during grasping.

Phalanges

The maximum loads at each joint were calculated, and appropriate bearings selected in each case. Shielded bearings were used wherever possible, to try and limit the ingress of dirt and grit into the bearings. Unshielded bearings were used in the main pivot joint to reduce the width of the finger, as shielded bearings would have put the finger outside the width constraint. Flanged bearings were used wherever the bearing was wider than the phalange plate to locate the bearing, and also so that the same bearings could be used for a carbon fibre finger. For the carbon fibre finger, the fibres need to be wrapped around spools and the flanges will act as one side of the spool. This is described in more detail in section 6.2.1 (page 74). Circlips were chosen to retain the bearings on the finger pivot pins to minimise the width of the finger.

Actuator Blocks

The only criteria used to select the radial support bearings for the lead screw was their inner and outer diameters. They were both required to have an outside diameter of 10 mm so as to sit in the reamed bore which also houses the 10 mm diameter motor and gearbox. This ensures good alignment between the gearbox output shaft and the screw. Since the radial load on the screw was expected to be almost negligible the load rating of these bearings was not a consideration.

The thrust bearing however needs to carry the full load on the screw when the finger is applying maximum gripping force. With the Minimotor motor the 40 N axial load (see Appendix B, page 91) on the screw under full motor torque is well within the 780 N capacity of the 8 mm thrust bearing chosen. Even if the Maxon motor were used the axial load would only reach 454 N.

4.2.3 Drive Screws and Nuts

It was decided to make custom lead screws for the finger in-house. An $M4 \times 0.7$ ISO metric fastener thread was chosen for the screw because it was extremely easy to manufacture using standard dies, and standard taps for the nuts. The dies could be opened up slightly to make the thread a tight fit inside the nut to reduce backlash.

One other option considered however was to use miniature ball screws to drive the fingers. The ball screws have a very high efficiency (about 90%) when compared to the M4 metric screw fastener thread which has a calculated efficiency of 38%. This makes using ball screws to drive the finger a very attractive proposition, since the tip force would be more than double what is achieved using a plain threaded screw. A 3 mm diameter, 1 mm lead ball screw [NTN Corporation, 1991] is available which, with a dynamic load capacity of 330 N will easily handle the 40 N load applied when the Minimotor motor is generating maximum torque. A 4 mm nominal diameter ball screw [THK Co., 1989] with a lead of 1 mm is also available which, with a dynamic load capacity of 588.6 N is suitable for use with the Maxon motor when it is generating a maximum load of 453.7 N on the screw. The problem with these screws however is their size and their price (the THK ball screw costs around $700). The 3 mm diameter screw has a 9 mm diameter nut that would fit into the space available for the finger, but the nut has a 22 mm diameter flange that would have to be cut off to make it fit. The nut is also long and heavy when compared to the nut on the M4 screw.

4.2.4 Materials

Strength to weight ratio was one of the major considerations when selecting materials for the finger. Table 4.2 summarises the reasons for selecting the materials used for the different components. Some of the phalange side plates on the first prototype were made out of acrylic so that the linkage mechanism could be seen easily when the finger was being demonstrated and tested. This worked very well. The linkage mechanism operating the phalanges can even be seen working when the finger is placed on an overhead projector.

Table 4.2 Motivation for material choices.

MATERIAL	COMPONENT	REASON
Stainless Steel	pivot pins screws	Good strength, reasonably easily machined, corrosion resistant.
Acetyl/Delrin	nuts coupling centre piece	Light weight, self lubricating/low friction, good strength.
Acrylic/Perspex	rocker proximal phalange	Transparency - so can see how mechanism works. Light weight.
Aluminium	medial & distal phalanges	Strength, low weight, thickness available.
	actuator bodies	Good thermal conductivity, low weight, easily machined for fine details.

4.2.5 Motor Drive Options

A number of drive options are available for the finger motors, most being dependent on the type of motor control desired. The options considered for the Minimotor motor were:

- Batteries - manual switch control.
- 1A single chip driver - PWM position control.
- Constant current analog drive.

Batteries - manual switch control

The finger was initially set up using a battery pack and two DPDT switches, one switch to control the direction of each motor.

Prosthetic devices in current usage are sometimes operated by mechanical switches, which are often operated via a shoulder harness. However the complexity of the finished hand requires a much more complex control system than is possible using this method. However the battery pack was very useful in demonstrating the finger as it was very simple and very portable. It was demonstrated in this way at IFToMM 95 conference (*The International Congress on the Theory of Machines and Mechanisms*) in Milan, Italy.

1A Driver Chip - PWM Position Control

The Motorola MC33030 [Motorola, 1985] is a monolithic DC servomotor controller. It is designed to perform closed loop position control for a fractional horsepower DC motor and contains a 1 A power H-switch to drive it. It senses actuator position by voltage feedback. By comparing a PWM 0-5 V signal with a fixed 2.5 V input reference, the chip is operated as a

PWM servo drive. The chip also provides over current protection which is very important with the Minimotor motor.

In the case of the Canterbury finger, the DC motor is fitted with a magnetic encoder that gives a ten pulse-per-revolution quadrature output. To control the motor, this was fed into a Universal Pulse Processor (UPP) card [Dunlop & Murphy, 1993] (this card is described in more detail on page 61). This card reads the quadrature output from the servomotor, and outputs the appropriate PWM voltage to the driver chip to drive the motor in the desired direction, until the required position is reached.

The finished Canterbury finger has not been operated with this controller because it does not provide motor torque control, which was considered important for a hand.

Constant Current Control Drive

A constant current control drive was developed in the Mechanical Engineering Robotics Laboratory at the University of Canterbury for the Canterbury finger.

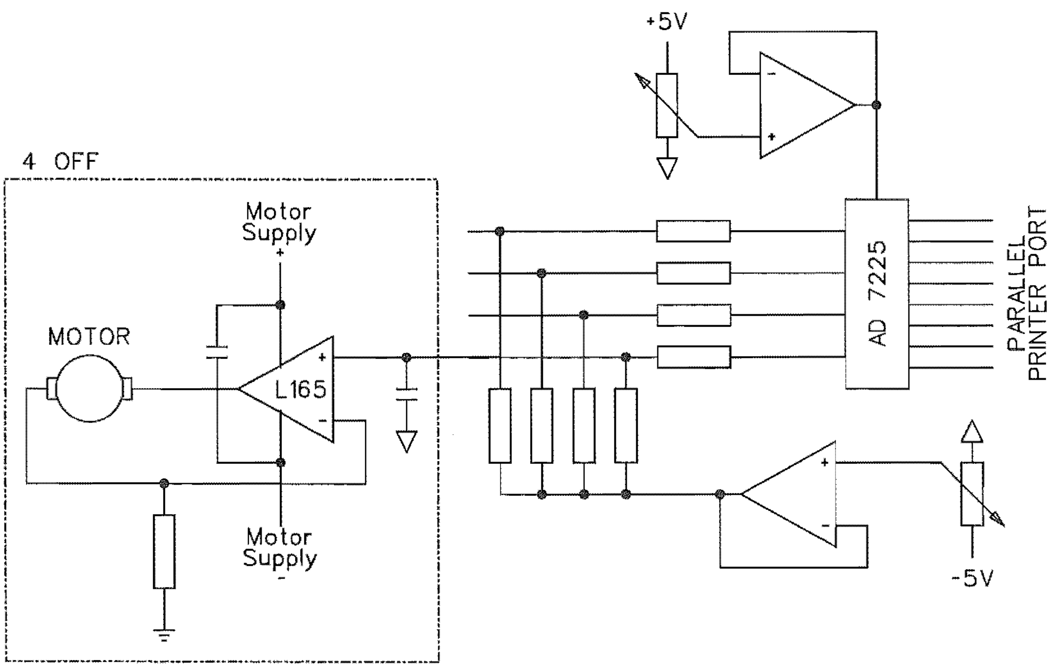


Figure 4-4 *Schematic drawing of constant current control drive.*

The intention was to control the current, and hence the torque output of the motor. Thus it is possible to control the force output at the finger tip. The prototype drive has been designed to drive four motors (Figure 4-4). It consists of an Analog Devices AD 7225 quad digital-to-analogue converter (DAC) and four 3 A power operational amplifiers (op-amps). The digital input pins on the DAC are connected to the parallel printer port on an IBM compatible PC and each of the four analogue outputs drives an SGS-Thompson [1988] L165 3 A power op-amp. Each op-amp in turn drives one of the DC servomotors.

4.3 Manufacturing Methods

The finger was designed and drawn using MicroStation® from which it is possible to transfer the design to Mastercam® [CNC Software, Inc.] to create Numerical Control (NC) programs for Computer Numerical Controlled (CNC) machines. This Computer Aided Manufacture (CAM) technique was used to show that the Canterbury hand could be produced quickly and easily, with minimal set up time since conventionally manufactured prosthetic hands are expensive partly because of high set up costs and short production runs. The side plates and links of the finger were stacked and cut two at a time using a Fanuc CNC Milling Machine. This machine was used to cut the Metacarpal Blocks as well (Figure 4-5). The MP joint pivot bracket was manufactured using a Fine Sodick CNC EDM Wirecut Machine (Figure 4-6). Use of the CNC machines allowed more complex shapes to be used for the metacarpal blocks and phalange plates, and allowed the addition of holes for weight reduction without greatly increasing the manufacturing time, as would happen if a manually controlled machine were being used. The finger pivot pins, spacers and spacer washers were turned manually on a small tool makers lathe. The manufacture of the pins required high precision, with dimensions of $\varnothing\, 1.5^{+0}_{-0.007}$ mm on the bearing surfaces of the pins, and the requirement to cut $\varnothing$ 1.2 mm circlip grooves in the $\varnothing$ 1.5 mm ends of some of the pins. Spacer washers that were consistently 0.125 mm thick were also cut from free cutting aluminium bar stock.

137 components make up the Canterbury finger and of these 72 were bought in and 65 were manufactured in the University of Canterbury Mechanical Engineering Workshops. 32 % of these manufactured components were fabricated using the CNC machines, so a reasonable proportion of the finger manufacture is already automated.

The components that make up the Canterbury finger are shown in Figure 4-5 and Figure 4-6.

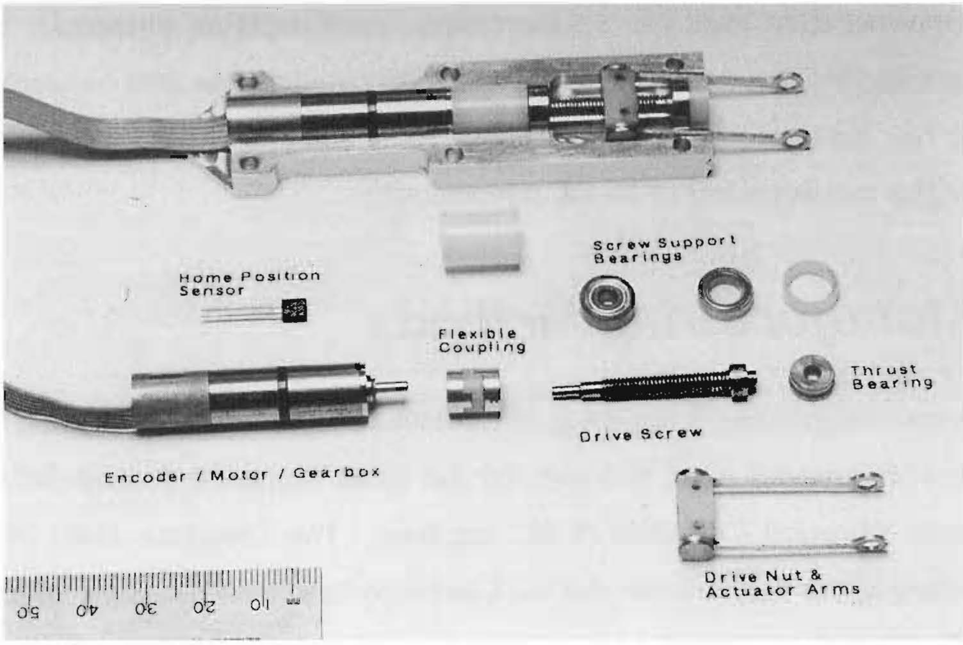


Figure 4-5 *Metacarpal blocks with drive components in place.*

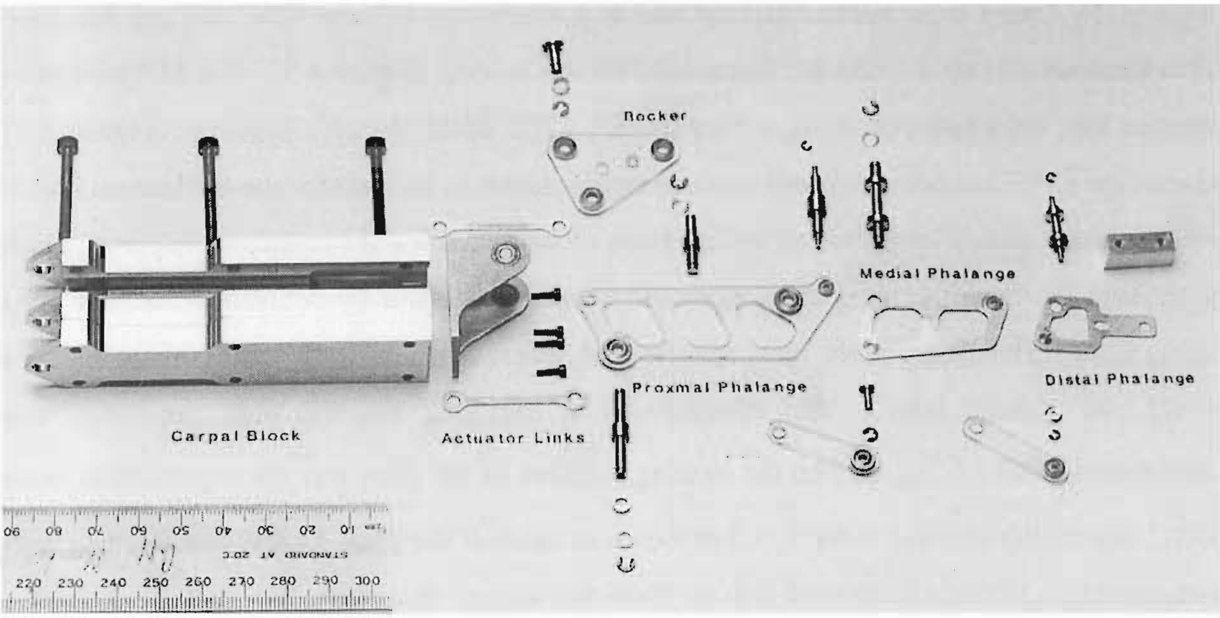


Figure 4-6 *Finger components.*

4.4 Finger Control

The constant current drive described in section 4.2.5 is used to run the two motors which drive the finger. This constant current drive is controlled directly via the parallel port of a PC. Position feedback is provided by the quadrature pulse encoders at the end of the DC motor. The pulses are counted by a UPP circuit on a printed circuit board (PCB) plugged into a PC ISA bus slot.

The UPP board is a recent development of the Mechanical Engineering Department at the University of Canterbury. It carries two Hitachi HD63140 universal pulse processor chips. These each carry twenty-four 16 bit counters that can be configured in many ways. In this case they are being used to read the quadrature output from the motor encoders. They also carry 10 Analog to Digital Converters (ADC's) and 16 I/O pins for the counters. In the future, force feedback via the ADC channels will provide more accurate force control for the finger.

It is proposed that a complete hand be controlled using two UPP boards. A six fingered hand, as has been proposed [Dunlop & Ward, 1995], would require 30 inputs to 15 quadrature counters, one input shared for every five motors to allow a datum to be established for each servo, and 15 inputs to monitor the motor drives, thus using a total of 48 I/O pins, or three UPP chips. A breakdown of the motors required is provided in Table 4.3.

Table 4.3 *Motors required for a six fingered hand.*

Two for each finger or thumb, for six digits.	12
One motor for swinging each thumb.	2
One last motor to spread all the fingers together.	1
Total	15

If 6 DOF forces were to be measured for each finger, this would still only use 36 out of the 40 analog inputs available.

4.5 Conclusions

The kinematics of the Canterbury finger were checked using both a mathematical model of the finger developed using MATLAB™, and a parametric model in the CAD package, MicroStation®. The working region of the finger tip was defined, and the position of a singularity in the mechanism was identified.

A selection process that included calculation of tip force and an estimation of joint forces was carried out to choose bearings, motors, transmissions, and materials for the finger. This information was used to produce a detailed design of the finger and help define the production processes. As many components as possible were manufactured using CAM techniques to show that the Canterbury finger could be quick, easy and cheap to manufacture.

The control system used for the prototype finger, which incorporates motor torque control, has been described, and its extension to a six fingered hand has also been proposed.

CHAPTER 5

First Prototype

The first prototype of the Canterbury finger was completed at the beginning of August 1995. This chapter describes the performance tests carried out on the finger and discusses the results. The measured performance characteristics are compared to those calculated during the design phase. The performance of the Canterbury finger is also compared to that of other research hands, including the Belgrade/USC hand. Some of the limitations of the design are described and modifications that were made to the finger after it was built are also presented.

5.1 First Iteration

The first prototype of the Canterbury finger was completed in August 1995 to present at the IFToMM 95 conference (*The International Congress on the Theory of Machines and Mechanisms*) in Milan, Italy. The finger had not been tested before this conference and some short cuts were taken to have it operational in time. Temporary couplings (pieces of plastic tubing) were used to connect the gearbox output shafts to the main drive screws because the flexible couplings specified had not been built at that stage. A design tolerance fault was found in the design of the main pivot bracket when the finger was assembled, but since there was no time to have a new bracket built, the original was modified as a temporary measure. Initially the finger was powered by a pack of four 1.5 V dry cell batteries, and controlled using two double pole double throw (DPDT) switches since control software for the constant current drives had not been completed. A suitable portable computer for control has yet to be purchased and some extra circuitry to interface the drivers and UPPs will also be needed before a fully working finger can easily be demonstrated outside the laboratory.

The only problems encountered with the finger while travelling with it in Europe were broken wires on the battery pack. The temporary couplings were also starting to slip by the end of the two month tour.

The battery power pack worked well as the impedance of the batteries was such that the current in the motors did not exceed the rated maximum current, even at stall.

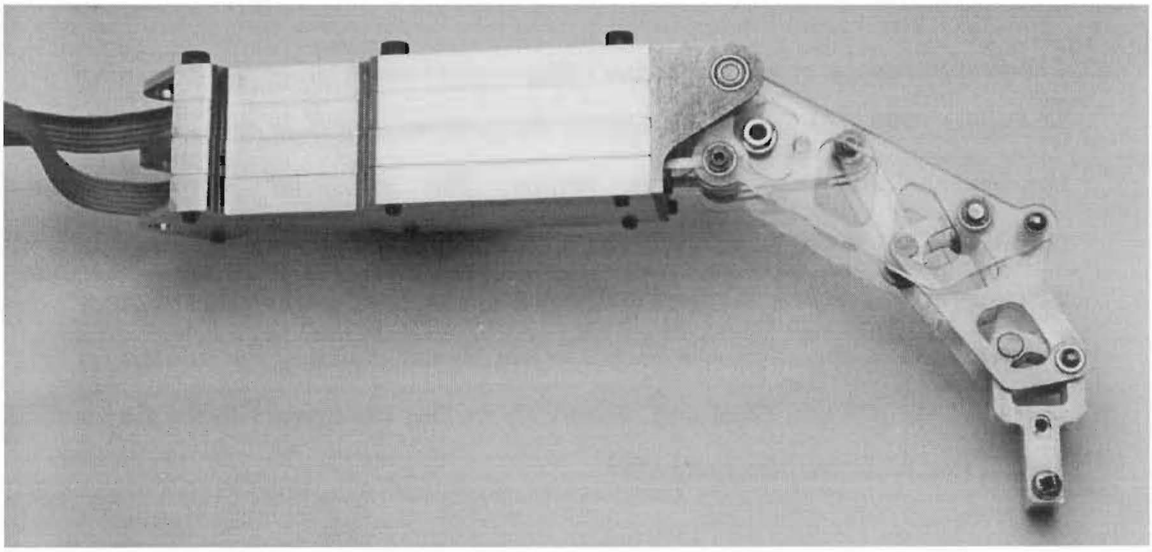


Figure 5-1 *The completed Canterbury finger.*

5.2 Required Modifications and Improvements

A number of small modifications and improvements were carried out on the finger to improve its operation. Some areas still need to be addressed to get the finger performing as well as intended.

- Because of a design fault in main finger pivot, material had to be removed from the inside face of the pivot bracket to get proximal phalange to fit, and so that the finger could attain its full range of movement.

- The backlash present in the linkage mechanism, giving up to 4 mm of free play at the finger tip, seemed excessive. A number of causes were found for this. When the finger was loaded, the rocker plates tended to move apart. This was temporarily fixed by putting a spacer between the plates and clamping them together. A one piece replacement rocker is being designed.

- The manufacturing tolerances on the holes in the phalange side plates and driving links were not tight enough, causing some of the pivot pins to be very loose in the holes.

Some holes had also been drilled oversize and had been fitted with spacers. The spacers and pivot pins were bonded in place with Loctite wherever it was possible to do so without making the finger impossible to disassemble. Manufacturing the links with correct tolerances will reduce the backlash and improve the performance.

- The lead screws were manufactured incorrectly – the threaded section was not concentric with the bearing sections at either end. This caused the nuts to bind on the sides of the guide slot in the metacarpal housing. The nuts were carefully thinned to give them space to move, however the lead screws should be re-manufactured. The thread on one of the nuts quickly became loose and contributed to the backlash in the finger.

- New couplings were fitted between motors and lead screws to replace the temporary pieces of plastic tubing. This allowed the motors to apply maximum torque to the lead screws without slipping.

After carrying out the modifications listed above and fitting the new couplings between the motors and the screws, an adapter board was designed and built to feed the signals from the quadrature encoders on the finger motors into the UPP card contained in an IBM compatible PC. This adapter board also feeds power from the constant current control drive to the supply pins on the motor header plug. The arrangement is shown in Figure 5-3. A Motorola MC14584 Hex Schmitt Trigger was used to buffer the encoder output from the encoders and improve their drive capability so that a much longer cable could be fitted between the encoders and the UPP board.

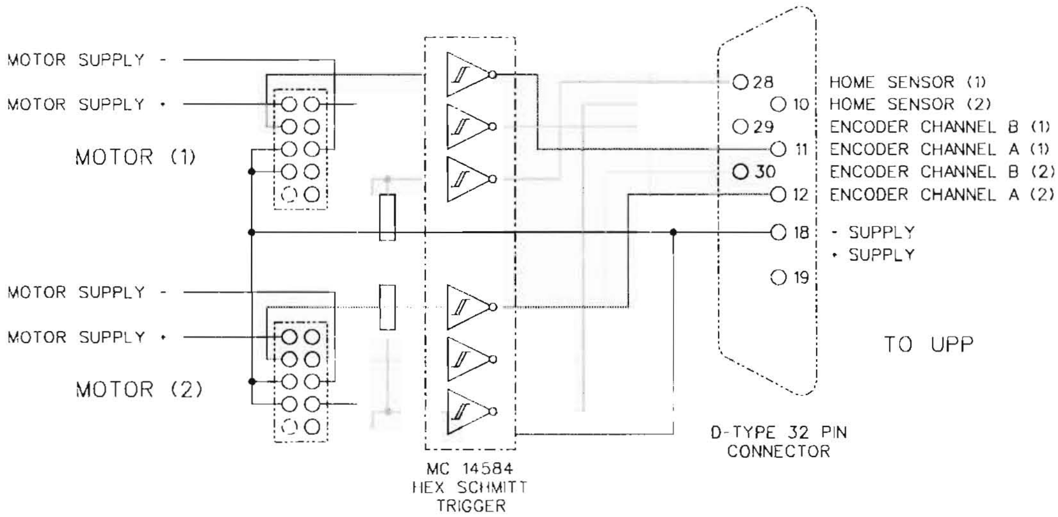


Figure 5-2 *Schematic drawing of the motor connection adapter board.*

The adapter board also carries pull up resistors for the two Hall effect switches that are to be fitted to the finger. These will be used as a reference point for setting the encoders when the finger is first powered up. The Schmitt trigger also buffers the output from the Hall effect switches.

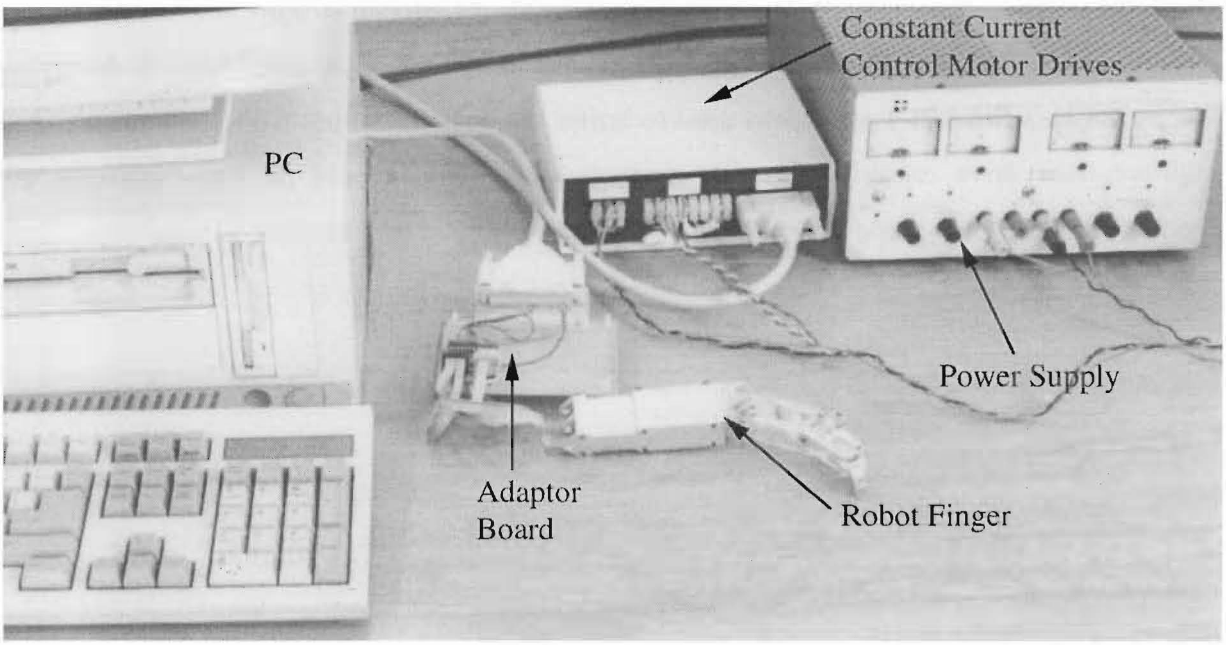


Figure 5-3 *Finger connected to control hardware.*

The finger was now ready for use and the tests carried out are described in the following sections.

5.3 Measured Performance of Robotic Finger

A set of criteria were developed to try and quantify the performance of the Canterbury finger so we could compare the results obtained against our original specification, the performance of the human hand, and against some of the other mechanical hands.

5.3.1 Performance Criteria

The important performance criteria for a robotic finger were deemed to be:

- Maximising force output. A minimum tip force of 5N is desired, since in a three fingered grasp, with two fingers opposing a thumb running at half the speed, but producing twice the tip force, a grip force of 10N could be achieved. This is stated by Kyberd [1995] as being the maximum grip force required for 80% of grasps.
- Maximising speed of operation.
- Having high dexterity.

For a prosthetic hand these former criteria were important, but so also were:

- Being human sized.
- Minimising weight.
- Having a low power consumption.
- Being aesthetic appealing.

Force output is quite easily measured using a set of scales, and speed of operation can be timed reasonably well with a stopwatch. Dexterity however is a little harder to quantify. Mobility of the finger is a much easier parameter to measure. Again size and weight are easy to measure, but a true test of power consumption, especially for a prosthetic device that is not performing a set of predefined tasks like a robot often would be, is a little more involved. Determining expected power consumption would require the hand to be used by a person, and the power usage recorded over a period of time. Aesthetic appeal is very much up to the individual, but here we will take this as meaning how closely the finger resembles the form and movement of the human finger.

5.3.2 Test Procedure

Measurement of force output

The finger was clamped in a vice with the tip sitting just above a knife edge that was resting on a set of electronic scales, as shown in Figure 5-4. The scales were such that the load could be applied anywhere on the weighing surface, and they would still give the same reading. This layout was designed to give the force output of the finger at its tip. The finger was connected to the constant current drive and the UPP card in an IBM compatible PC via the adapter board. The position control program written for the finger (see Appendix C, page 101) requests values for the maximum output torque to be provided, and the final position for the finger tip. Maximum torque was supplied to the motors to generate maximum force in the finger tip when it contacted the knife edge in the fully extended position. As soon as the reading on the scales had stabilised, the drive to the finger was turned off to prevent the rotor windings burning out, since we were supplying the peak permissible current, not the peak continuous current. These measurements were repeated five times, driving the top motor only, the bottom motor only, and both motors together, to get an average force output in each case.

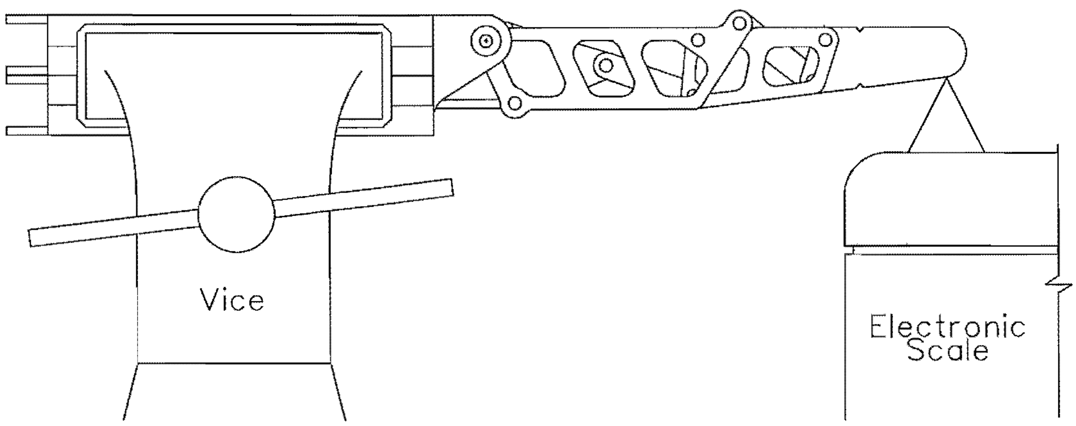


Figure 5-4 Test rig layout.

Measurement of speed of operation

A stopwatch was used to measure the time that it took for the finger to travel from its fully open to its fully closed position with full current applied by the motor drive.

5.3.3 Results

Force Output

The force obtained at the finger tip is 4.5 N using either the top or bottom motor, which is very close to the predicted value of 5.4 N (see Appendix B, page 93). Using both motors together we observed a tip force of 5.0 N. In the arrangement proposed with two fingers opposing a thumb, we would expect to achieve the desired peak grip force of 10 N.

Speed

Under no load conditions it was calculated that the Canterbury finger would take a minimum of 1.05 seconds to move from the straight position to the fully curled position, and closure times of approximately 1 second were observed in the laboratory.

Weight

The finished finger weighs 207.5 g, not including controllers or power supplies.

Size

The assembled finger and actuator pack is 222 mm long. The actuator pack is 118 mm long and the finger is 110 mm long. Its maximum width is 24 mm, across the metacarpal block, and its maximum depth is 28 mm, also across the metacarpal blocks.

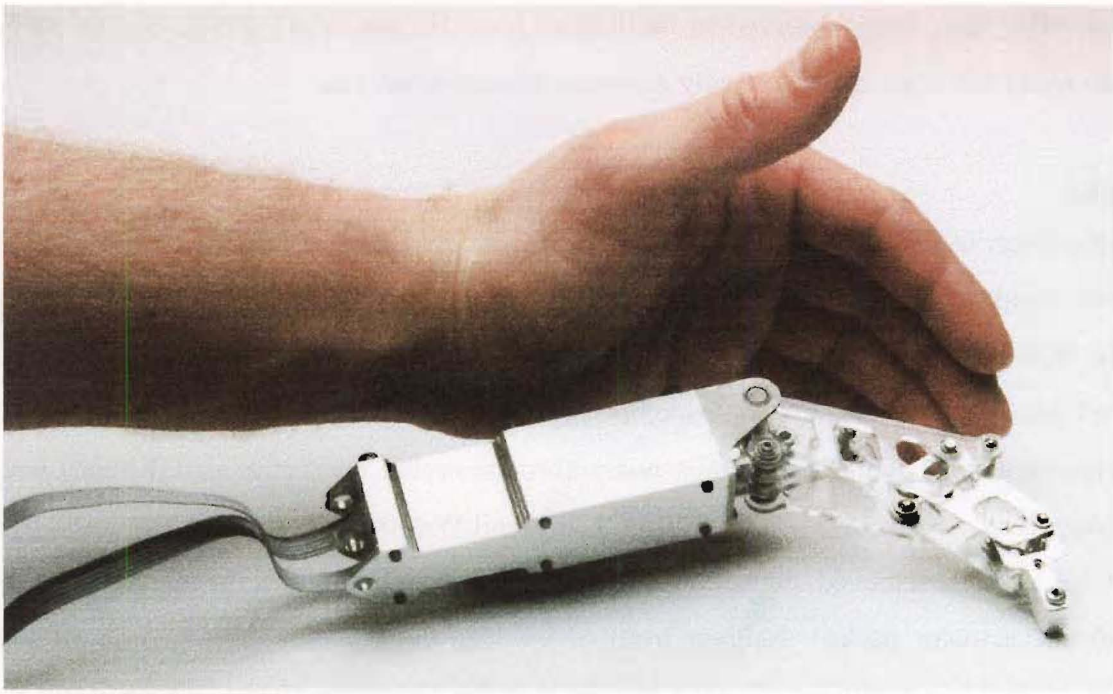


Figure 5-5 *The completed Canterbury finger next to a human hand.*

5.4 Discussion

Force Output

The force required for 80% of grasps is 10 N [Kyberd, 1995] yet the Canterbury finger produces only half of that. However, as discussed in section 4.2.1 a 10 N grip force can be achieved using two fingers to oppose a thumb running with a higher gear ratio, and hence with twice the tip force, but at half the speed. Of the research hands that force information has been obtained for, most produce around 20 N at the finger tip. The Hitachi hand is one of these. It however weighs 4.5 kg so its power to weight ratio (4.4 N/kg) is less than half that of the proposed Canterbury hand (10 N/kg). This is still a much lower force output than commercially available prosthetic hands which produce 85 – 120 N grip force and have a power to weight ratio of 185-240 N/kg. A lot of work needs to be done on the Canterbury hand if it is going to match this kind of performance.

Speed

A closing time of 1.05 s is slower than the human finger that can close in around 0.4 seconds or less, but is faster than the Belgrade/USC model I and model II hands which take approximately 2 seconds to close fully. Some of the tendon operated hands run at much faster speeds for small movements, the highest being 20 Hz for the Utah/MIT hand, as stated in Rosheim [1994], but the time taken for full finger closure is not given. Finger tapping rates of around 10 Hz have been observed in the human hand [Bekey et al., 1990], but as we have already noted full scale motion usually occurs at a much lower rate.

Weight

A single finger weight of 207.5 g would give a five fingered hand weighing 1037.5 g, and a six fingered hand weighing 1245 g. This is heavy compared to an average human hand that weighs 400-500 g, but is a lot lighter than any of the other research hands that we have collated data on. The lightest anthropomorphic hands listed weigh 4.5 kg (The Anthrobot-2 and Hitachi hands), while the lightest non-anthropomorphic hand (the USTB hand) weighs 3 kg (Appendix A, page 87). Two hands, the JPL and WABOT-2 hands, do seem to be lighter than what we have achieved, but it must be remembered that the figures for these hands do not include the actuator packs. Judging from of the size the actuator pack for the JPL hand (Figure 2-13) it is actually significantly heavier than the Canterbury hand. There is still some scope for reducing the weight of the Canterbury finger. One design considered by Traub

[1996] reduces the weight of the finger by 60 g by removing unnecessary material from the metacarpal blocks. This reduces the projected weight of the five fingered hand to 737.5 g, and the six fingered hand to 885 g.

Current commercially available prosthetic hands tend to weigh around 500 g so quite a bit of work is required if the Canterbury hand is going to match this weight. Also because the apparent weight of a prosthetic limb to an amputee is higher than its actual weight it would be desirable to get the weight of a future hand well under 500 g.

Size

The size of the finished Canterbury finger is very similar to an average human finger, as can be seen in Figure 5-5. The metacarpal blocks are only marginally longer than the human metacarp and are the same width and depth. The finger itself has the same dimensions as the average human finger, as lined out in the design specifications. At only 222 mm long the Canterbury finger is shorter than any other finger that this data has been obtained for.

Aesthetic appearance

Apart from its quite square cross section, when it is straight the proportions and appearance of the Canterbury finger are very similar to a human hand, and its motion seems quite natural. However the connection point for the link driving the distal link protrudes from the proximal link, and when the finger is curled this protrusion becomes quite noticeable. Addition of a shaped and padded glove would remove most of the effect of the square cross section, but would not be enough to hide this lumpy knuckle. It would require a redesign of the finger linkage mechanism to either minimise or remove this protuberance. The distal link has been designed to have a shaped tip fitted, and this will improve the appearance of the finished finger.

Dexterity

With a total of 12 independent DOF for a five fingered hand the Canterbury hand will have a similar level of dexterity to any of the tendon operated anthropomorphic hands reviewed in chapter 2, and a higher level than most of the direct driven anthropomorphic hands reviewed. The tip of the Canterbury finger can reach any point in its two dimensional work space, rather than just following a line like the tips of the fingers on the Southampton and Belgrade/USC hands. This allows the Canterbury finger to follow the contour of any object being grasped much better, and also allows it to perform more complex manipulations.

The Canterbury finger can rotate through 52° in the MP joint, 60° in the PIP joint and 66° in the DIP joint. Although this range of movement of meets the specification laid down by Magnier and Monier [1995], it is not as great as for the human finger, given in Rosheim [1994] as being 90° pitch in the two interphlangeal (IP) joints and the MP joint, and 25° yaw at the MP joint (first knuckle) of each finger.

5.5 Detrimental Effects of the Singularity

If the proximal phalange is fully flexed (fully curled) and the medial and distal phalanges are flexed until the singularity is reached, extending the proximal phalange will break the linkage pulling the upper actuator links out of the rocker. This happens due to the coupling between the two degrees of freedom. When the singularity occurs the medial and distal phalanges lock solid. Trying to extend the proximal phalange tries to pull the links past the point where they locked, and the force in the links rises rapidly. By limiting the travel of the nut on the upper screw to less than 9.38 mm ensures that a singular point is not reached when the proximal phalange is fully extended, and flexing the proximal phalange tends to move the linkage away from this singularity rather than towards it.

It is possible that the linkage could be modified so that it is not possible to reach any singularities, and this would also tend to give a slightly larger working area.

5.6 Conclusions

A prototype finger has been built. A number of minor modifications were made to the finger after it was first assembled, and a simple control program was written to allow the finger to be tested. Test results show that it produces a maximum tip force of 5.0 N and will travel through its full range of movement in approximately 1.05 s as required by the design specification. It is similar in proportion to a human hand and is much lighter and more compact than the fingers of existing robotic hands that have a similar high level of dexterity.

CHAPTER 6

Conclusions and Suggestions for Further Research

This chapter summarises the research presented in this thesis, suggests some improvements that could be made to the design, and discusses the merits of each. Suggestions for future research are then made.

6.1 Results Achieved

From the study of existing mechanical hand designs it has been concluded that linkage operated hands are the easiest to drive and control, and although cable operated hands tend to be faster and have a higher degree of dexterity, they suffer problems with friction and compliance in the cables. The Belgrade/USC hand was taken as a good example of a linkage operated hand that has low dexterity and is straight forward to operate. Two areas of possible improvement in its operation led to the conceptual design of the Canterbury finger.

The conceptual design of the Canterbury finger was used as the staring point for the development work carried out in this thesis. From this conceptual design a plan for the development of a working finger was produced. A kinematic model for the Canterbury finger was developed, the working region of the finger tip was defined, and the position of a singularity in the mechanism was identified. Using this information the force at the finger tip was calculated, and an estimation of the joint forces was made. This allowed components such as motors and bearings to be chosen for the finger, and a detailed design of the finger to be made. It was also decided to manufacture many of the components of the finger using CNC machines to show that the Canterbury finger could be manufactured quickly, easily and cheaply.

The control system to be used for the Canterbury finger, which incorporates motor torque control, has been described and its extension to a six fingered hand has also been proposed.

A prototype of the finger was built. After some initial testing a number of minor modifications were made to the finger. A simplified control program was written to allow the finger to be tested more rigorously. Test results show that the Canterbury finger produces a maximum force of 5.0 N at its tip, and will travel through its full range of movement in approximately 1.05 s.

Thus, a human sized finger has been produced, for use as either a robotic end-effector or a prosthetic hand, that is compact and lightweight. Although it does not compare to the human hand, it does rank favourably when compared to existing mechanical hand designs.

6.2 Suggestions for Future Work

A number of areas of improvement are seen for the finger to overcome its limitations as mentioned in section 5.4.

- Reduce weight:
    - remove excess metal form the metacarpal blocks.
    - manufacture links from carbon fibre
- Increase finger tip force:
    - use more powerful motors
    - increase transmission efficiency
- Improve aesthetics:
    - rearrange linkage mechanism to remove distal protuberance from the proximal link.

Further development work is also required to enable the finger to be assemble into a working hand.

6.2.1 Weight Reduction

The design of the metacarpal blocks is reasonably basic. A lot of material can be removed from these to reduce the weight of the finger. As mentioned in section 5.3.3 Traub [1996] has already produced a preliminary design for the metacarpal blocks that reduces their mass by 60%.

A scheme has been proposed whereby the finger phalanges and linkages could be manufactured from a carbon fibre composite material to minimise the weight and increase the stiffness of the finger. Carbon fibre cloth can easily be added to join the pairs of phalange side plates. This would stiffen the structure and provide a much larger gripping surface for the finger.

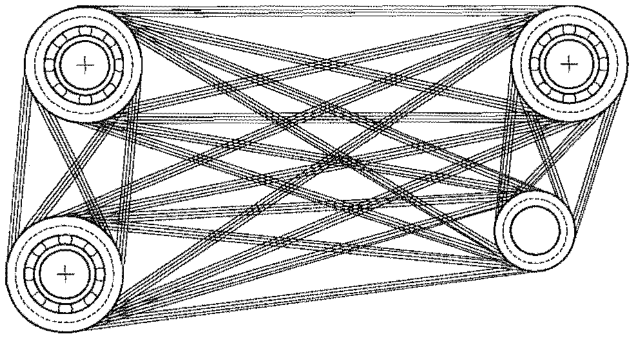


Figure 6-1 *Pictorial view of carbon fibre medial link*

The bearings selected for the current finger were chosen with flanged outer races to make manufacture of a carbon fibre finger simpler. The bearings are bolted, flange side up, onto a flat plate at the correct spacing for each joint. The flanges stop the wet fibre sliding off when winding it around each of the bearings.

6.2.2 Increasing Finger Tip Force

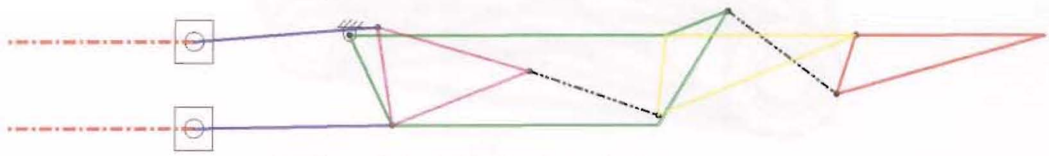
A study is already underway to optimise the link lengths and pivot point positions to try and improve the kinematic efficiency of the finger [Bain, 1996].

After studying the design of the Miniac actuators used to drive the Omni hand [Rosheim, 1994] it was discovered that using a multiple start screw to drive the finger, instead of a single start screw currently employed, would improve the overall transmission efficiency of the finger drive mechanism. Using the Finger Performance spreadsheet it was found that using a three start screw with a 0.7 mm pitch (giving a lead of 2.1 mm), and increasing the gearbox ratio to 64:1 to maintain a similar finger tip speed, would give power increases of between 12 % and 24 % (Appendix B, page 91).

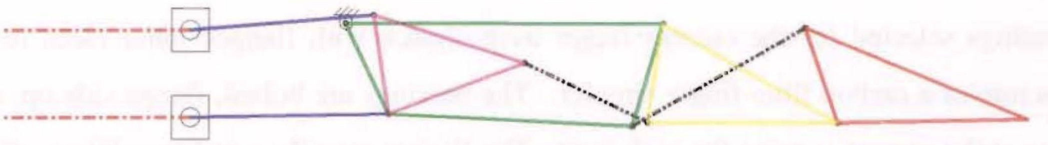
Therefore it is recommended that a three start screw and nut, with the same 0.7 mm as is currently being used, be manufactured and tested in the current finger to see if the gain in efficiency is as significant as is suggested by the spreadsheet calculations. The 16:1 gearbox currently used on the motor would have to be replaced with a 64:1 gearbox to maintain a similar finger speed.

6.2.3 Improving Aesthetics

The finger optimisation work being carried out by Bain [1996] is designed to minimise the protrusion of the extension to the proximal phalange, but it will not remove it completely. An alternative link arrangement has been devised that removes this protuberance completely (Figure 6-2).



(a) the original Canterbury finger.

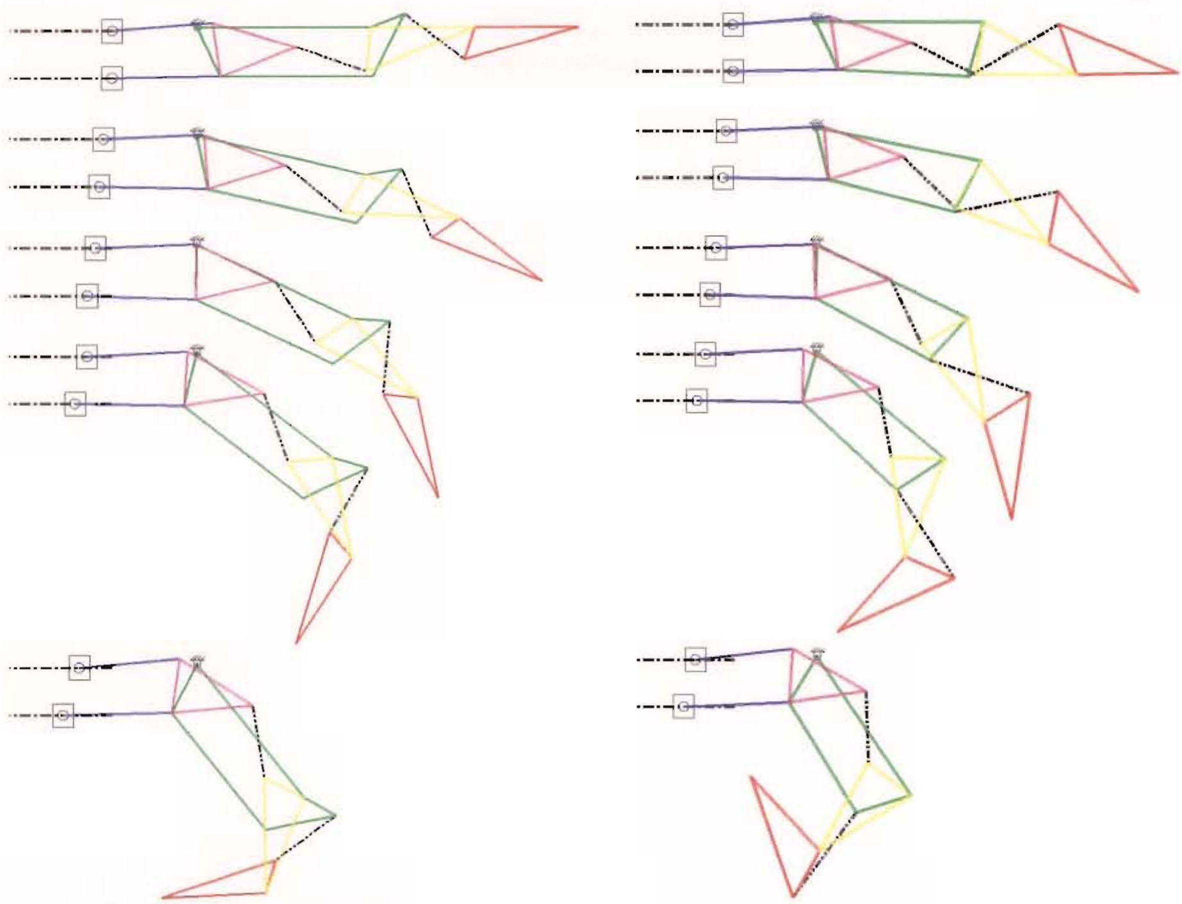


(b) a new linkage layout to improve the finger profile.

Figure 6-2 *An alternative linkage layout to improve the aesthetics of the Canterbury finger*

The primary aim of this modification to the finger linkage design is to improve the aesthetic appearance of the finger, but it appears that the working range of the finger tip will be increased (Figure 6-3) and some preliminary investigation work done in co-operation with Andrew Bain suggests that the force output of the finger will also be increased.

These results suggest that further work should be carried out investigating this design.



(a) existing linkage design *(b) new linkage design*

Figure 6-3 *The mobility of this alternative finger design compared to the original Canterbury finger.*

6.2.4 Additional Design for Hand Assembly

Some additional work is also required before the existing finger, or any new design of finger, can be assembled into a complete hand: a mechanism needs to be designed to adduct and abduct the thumb; another mechanism is needed to spread the fingers; tactile and force sensing and control is required for the fingers; and before the Canterbury hand can be properly considered as a prosthetic device a human / machine interface mechanism is required.

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Software Manufacturers

Bentley Systems, Inc, 690 Pennsylvania Drive Exton, PA 19341 U.S.A. OR Bentley Systems Pty. Ltd. Suite 8, 51 City Road South Melbourne, VIC 3205 AUSTRALIA	MicroStation® v5.0.95
Borland International, Inc. 1800 Green Hills Road P. O. Box 660001 Scotts Valley, CA 95067-0001 U.S.A.	Borland C++ v3.0
CNC Software, Inc. 344 Merrow Road Tolland Connecticut 06048 U.S.A.	Mastercam® Mill v4.0

The Math Works, Inc. 24 Prime Park Way South Natick, MA 01760 U.S.A.	MATLAB™ v4.2c
Wolfram Research, Inc. 100 Trade Centre Drive Champaign, IL 61820 U.S.A.	Mathematica® v2.2

Hardware Manufacturers

Interelectric AG Brünigstrasse 220 CH-6072 Sachseln/OW Switzerland	Maxon Motor - Drive components and systems
Minimotor SA CH-6982 Agno Switzerland	DC-Micromotors Gearheads Tachogenerators Encoders Drive circuits
Motorola Semiconductor Products Inc. Box 20912 Phoenix, Arizona 85036 U.S.A.	Semiconductor devices
NTN Corporation Head Office 3-17, 1-chome, Kyomachibori Nishi-ku Osaka, 550 Japan	Precision Ball Screws
THK Co., Ltd. 3-6-4, Kami-Osaki Shinagawa-ku Tokyo 141 Japan	Ball Screw Systems
Transicoil Inc. 2560 General Armistead Avenue Norristown, PA U.S.A.	DC Motors Brushless DC Servomotors

Appendices

Appendix A : Hand Comparison Spreadsheet

HAND	# Joints / Finger	# Joints / Thumb	Total Joints	Number of Fingers	Number of Thumbs	Total	DOF	Anthrop	Actuator	Transmission	Load Capacity	Actuator Bandwidth	Speed	Weight	Overall Length	Reference	Comments
Canterbury (robotic)	4	4	24	4	2	6	15	✓	electric	rigid links			1.05 s	1.2kg	222 mm		207.5 g/finger
Canterbury (prosthetic)	4	4	24	4	2	6	12	✓	electric	rigid links			1.05 s	1.0kg	222 mm		207.5 g/finger
Early Research Hands																	
Belgrade Prosthetic Hand	3	2	14	4	1	5	1	✓	electric	cable						Tomovic & Boni [1962]	Differential mech. (whiffle tree)
Okada	4	4	12	2	1	3	12	×✓	electric	cable						Okada [1986]	
Robot Hands																	
CTSD I	3	None	9	3	None	3	1	×	electric	cable						Rosheim [1994]	3 fingers equispaced @ 120deg. Differential mech.
CTSD II	3	3	9	2	1	3	3	×	electric	solid link						Rosheim [1994]	2 fingers opposing 1. Inc. wrist.
GE Handyman	5	None	10	2	None	2	6	×	electro hyd.	tendon (steel)						Rosheim [1994]	
Karlsruhe	3	None	9	3	None	3	9	×	electric	direct / timing belt						Wöhlke [1994]	DC motors driving harmonic drives!
Odetics	2	3	8	1	2	3	8	×	electric							Rosheim [1994]	2 speed transmission
Sarcos	0.5	2	3	2	1	3	3	×	hydraulic	hydraulic	22.7 kg					Rosheim [1994]	Fixed finger, spreading finger & 2 DOF thumb
Skinner Hand (MPMS)	4	None	12	3	None	3	5+	×								Andeen[1988]	For industrial assy. Funded by NASA for Skylab.
U.K.	3	None	9	3	None	3	9	×	electric	tendon						Guo et al. [1991]	Has rotating finger tips.
UPenn	2	3	8	1	2	3	8	×								Urlich, Paul & Bejcsy [1988]	Only have paper on prelim. design
USTB	4	5	14	1	2	3	8	×	Brushless DC	cables	2 kg			3 kg	318 mm	Congqinq et al. [1993]	
Cable or Tendon Operated Anthropomorphic Hands																	
Anthrobot-2	4	4	20	4	1	5	16	✓	electric	cables		3 Hz		4.5 kg	457 mm	Vanriper et al. [1992]	2 DOF wrist.
Hitachi	4	4	12	2	1	3	12	✓	SMA wires	cables	2 kg	(2 Hz)	90 °/s	4.5 kg*	700 mm*	Rosheim [1994]	* including forearm (actuator pack).
Jameson	4		8	2	1	3	?	✓	electric	tendons						Rosheim [1994]	similar to Utah/MIT hand, but with bevel gear wrist
JPL	4	4	16	3	1	4	16*	✓	electric	cable	2 kg (F. tip) 3.5 kg (T.tip)		~ 1 s	0.9 kg + act.		Jau [1995]	*not counting compliance actuators
Mitsubishi Heavy Industries	3	4	13	3	1	4	14	✓	electric ?	cable						Omichi et al. [1990]	assembles & disassembles std. 1500 lb check valves. 2 extra joints in palm.
Salisbury	3	3	9	2	1	3	9	✓	electric	cable	4.5 kg			6.6 kg		Rosheim [1994]	
Utah/MIT	4	4	16	3	1	4	16	✓	pneumatic (32)	tendons (288 pulleys)	3.18 kg (tip)	20 Hz				Jacobsen et al. [1986]	
Victory Enterprises				3	1	4	?	✓	electric	cable						Rosheim [1994]	
WABOT-2	3	2	14	4	1	5	14	✓	DC motors	cables		15 Hz		450 g*	224.5mm	Sugano & Kato [1987]	* plus actuators - keyboard player only
Direct Driven Anthropomorphic Hands																	
Belgrade/USC (model I)	3	Fixed	12	4	1	5	2	✓	electric	rigid links		0.6 Hz	~ 2 s			Bekey et al. [1990]	
Belgrade/USC (model II)	3	3	15	4	1	5	4	✓	electric	rigid links	2.2 kg	0.6 Hz	~ 2 s		266 mm	" " " "	
Belgrade/USC (model III)	3	3	15	4	1	5	6	✓	electric	rigid links	1.3 kg		0.7 - 0.8 s				
Omni-Hand	4	4	12	2	1	3	9	✓	electric	direct / links	6 kg/fin		1/2 "/s			Rosheim [1994]	2 DOF wrist.
Southampton	3	2	14	4	1	5	4	✓	Maxon DC motors	rigid links	120N grip force					Kyberd & Chappell [1994]	EMG control !! Double swingletree (whiffle tree) allows the 3 connected fingers to all contact object.
Commercially Available Myoelectric Hands																	
CAPP-II-TD																Patton '88, Wilson '89	from Kyberd et al. [1993]
Hosmer Dorance									electric								
MARCUS Tide	1	1	3	2	1	3	2	× ?	electric	direct ?							
MCA	2	1	5	2	1	3											
NU-VA Synergetic Prehensor																	
Otto Bock Electric Hand	1	1	3	2	1	3	1	✓	electric	rigid links	85 N		85 mm/s	460 g		Otto Bock [1986]	
Otto Bock Electric Greifer	1	1	2	1	1	2	1	×	electric	rigid links	15 N / 120 N		120 mm/s	500 g		Otto Bock [1986]	Has a 2 stage gearbox.
Steeper	1	1	3	2	1	3	2		electric								
UTAH Artificial Arm (Co.)																	
VANU								✓	electric								Proportional myoelectric control !
Viennatone MM3							1		electric				1 s				Austrian. Used by Kyberd to develop control sys.
Unknown																	
Dexter IIIB	4	4	20	4	1	5			Step motors	tendons		2 Hz					Used for sign language. 2 DOF wrist. Large external power pack.
Mark-1	4	4	20	4	1	5	16					5 Hz					
U.B.																	

Appendix B: Motor Selection Spread Sheets and Calculations

This appendix contains the Motor Comparison and Finger performance spreadsheets. The first section outlines the formulae used in the spreadsheet to produce the performance data displayed. Data not included in this calculations section was taken directly from the manufacturers specifications sheets, of from the finger design specifications.

B.1 Calculations for the Motor Comparison Spreadsheet

This spreadsheet was developed to compare the different packages available for driving the finger.

B.1.1 Motor Performance

Performance characteristics for each motor were calculated from the manufacturers data using formulae from Minimotor [1992].

Torque Output (T_B):

The torque output of the motor at speed N_B is given by:

$$T_B = T_S \frac{N_0 - N_B}{N_0} \tag{B.1}$$

where:

T_S = Stall Torque = 1.06 mNm
N_0 = No load speed = 17,600 rpm
N_B = Operating speed = 6,000 rpm, for example.

$$\therefore T_B = 0.699 \text{ mNm}$$

Current Demand (I_B):

The motor current demand when supplying torque T_B is given by:

$$I_B = \frac{T_B + T_f}{K_T} \tag{B.2}$$

where:

T_f = Friction torque = 0.03 mNm

K_T = Torque constant = 3.35m Nm/A

$$\therefore I_B = 217.5 \text{ mA}$$

Output Power (P_{2B}):

The power output of the motor at this operating point is given by:

$$P_{2B} = \left(\frac{2\pi N_B}{60}\right) T_B \qquad \textbf{\textit{B.3}}$$

$$\therefore P_{2B} = 0.439 \text{ W}$$

Motor Efficiency (η_B):

The electrical efficiency of the motor is found using Equation B.4:

$$\eta_B = \frac{P_{2B}}{V I_B} \qquad \textbf{\textit{B.4}}$$

where:

V = Operating voltage = 6 V

$$\therefore \eta_B = 33.6\,\%$$

B.1.2 Gearbox Performance

The torque transmitted by the gearbox was calculated for each drive package.

Torque output (T_{out}):

The output torque of the gearbox at operating point B is given by:

$$T_{out} = \eta_{GB} \left(\frac{N_{IP}}{N_{OP}}\right) T_B \qquad \textbf{\textit{B.5}}$$

where:

η_{GB} = the gearbox efficiency = 80 %
N_{IP} = the gearbox input speed = 16
N_{OP} = the gearbox output speed = 1

$$\therefore T_{out} = 8.94 \text{ mNm}$$

B.3 Calculations for the Finger Performance Spreadsheet

Using the motor performance data calculated in the Motor Comparison spreadsheet, the operating characteristics of the finger could be calculated for each operating point using each drive package.

B.3.1 Finger travel

Time taken for full travel of the finger (t_m):

$$t_m = \frac{60\, N_{IP}\, L_n}{N_B\, N_{OP}\, p} \qquad \textbf{B.6}$$

where:

L_n = distance travelled on screw n for full travel of the nut

n = 1 (bottom screw)

L_1 = 13.53 mm

p = pitch of screw thread = 0.7 mm

$$\therefore t_m = 3.20\text{ s}$$

B.3.2 Force generated at finger tip

The force generated at the finger tip was calculated using formulae developed for power screws by Deutschman et al. [1989].

Screw Efficiency (η):

The mechanical efficiency of a power screw is given by:

$$\eta = \frac{d_m \tan\alpha}{d_m\left[\dfrac{\cos\theta_n - f_s \tan\alpha}{\cos\theta_n + f_s \cot\alpha}\right] + d_{mb} f_b} \qquad \textbf{B.7}$$

where:

d_m = Mean diameter of the screw thread = 3.545 mm

d_{mb} = Mean thrust bearing diameter = 5.5 mm

f_b = Coefficient of friction in the thrust bearing = 0.006

f_s = Coefficient of friction in the screw = 0.08

θ = Thread angle = 30°

α = Helix angle of thread (°)

θ_n = Combined thread angle (°)

$$\tan\alpha = \frac{n\,p}{\pi\,d_m}$$

where:
n = Number of starts on the thread = 1
p = Thread pitch = 0.7 mm

$$\therefore \alpha = 3.597°$$

$$\tan\theta_n = \cos\alpha\tan\theta$$
$$\therefore \theta_n = 29.95°$$

$$\therefore \eta = 38\%$$

Force generated in the screw (F):

$$T_G = \frac{d_m F}{2}\left[\frac{f_s + \cos\theta\tan\alpha}{\cos\theta - f_s\tan\alpha}\right] + \frac{d_{mb} f_b F}{2} \qquad \textbf{\textit{B.8}}$$

where:
T_G = Gearbox output torque = 13.57 Nm
F = Force generated by the screw (N)

$$\therefore F = 39.59\,\mathrm{N}$$

Bearing stress on screw thread (σ_B):

$$\sigma_B = \frac{F}{\pi\,d_m\,h\,n_t} \qquad \textbf{\textit{B.9}}$$

where:
h = Depth of thread = 0.429 mm
n_t = Number of threads in nut = 8.6

$$\therefore \sigma_B = 0.966\,\mathrm{N/mm^2}$$

Bending stress on screw thread (σ_b):

$$\sigma_b = \frac{3\,F\,h}{\pi\,d_m\,n_t\,b^2} \qquad \textbf{\textit{B.10}}$$

where:
b = thickness of the thread at the root diameter = p/4 [Boundy, 1987]
= 0.7/4

$$= 0.175\,\text{mm}$$

$$\therefore \sigma_b = 17.43\,\text{N/mm}^2$$

Shearing Stress in screw threads (τ_{sc}):

$$\tau_{sc} = \frac{3F}{2\pi\, d_r\, n_t\, b^2} \qquad \textbf{\textit{B.11}}$$

where:

d_r = the root diameter of the screw = 3.141 mm

$$\therefore \tau_{sc} = 4.01\,\text{N/mm}^2$$

Shearing Stress in threads of nut (τ_{nut}):

$$\tau_{nut} = \frac{3F}{2\pi\, d_o\, n_t\, b^2} \qquad \textbf{\textit{B.12}}$$

d_o = the major diameter of the screw = 4 mm

$$\therefore \tau_{nut} = 3.15\,\text{N/mm}^2$$

Force transferred to the finger tip (F_T):

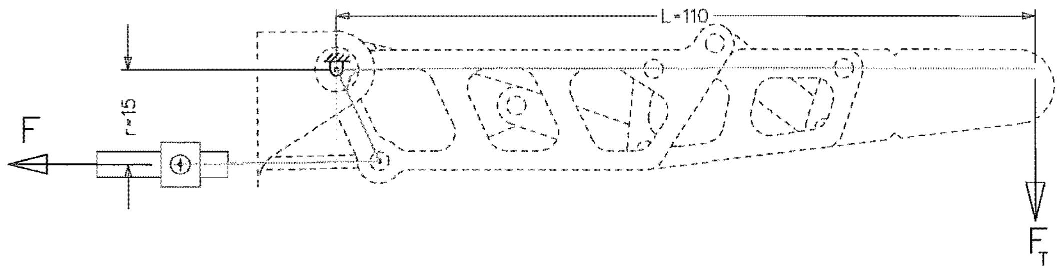


Figure B-1 *Finger geometry*

$$F_T = \frac{F\,L}{r} \qquad \textbf{\textit{B.13}}$$

where:

L = length of the finger = 110 mm
r = distance from finger pivot that screw acts at = 15 mm

$$\therefore F_T = 5.40\text{N}$$

B.4.1 Finger Travel

Leadscrew

	symbol	units		
Pitch	p	mm	0.7	
Diameter	D	mm	4	Using M4 ISO Metric Thread (for fasteners)
Nut Travel				
- top screw	L_2	mm	9.87	50 Degrees of movement in the Proximal Link of the finger (maximum travel) is given by 13.53mm of movement in the bottom leadscrew [Monier & Magnier, 1992].
- bottom screw	L_1	mm	13.53	

Screw Revolutions for Full Travel of Nut

Top Screw		rev	14.1
Bottom Screw		rev	19.33

Motor Revolutions for Full Travel of Nut

			Maxon Motor	Minimotor SA Motor	Minimotor SA Motor 2	Minimotor SA Motor 2	Minimotor SA Motor 3	Transicoil BDC Motor - 05LH24	Transicoil BDC Motor - 05LM24	Transicoil BDC Motor - 05LL24
Top		rev	233.8	225.6	129.3	129.3	197.4	225.6	225.6	225.6
Bottom		rev	320.5	309.3	177.2	177.2	270.6	309.3	309.3	309.3

Time for Movement

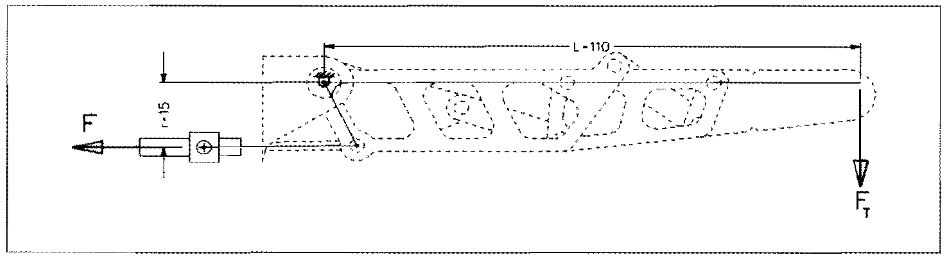
			Maxon Motor			Minimotor SA Motor			Minimotor SA Motor 2			Minimotor SA Motor 2			Minimotor SA Motor 3		
Operating Speed	N_B	rpm	13300	6000	3000	17600	6000	3000	15800	6000	3000	15800	6000	3000	11300	6000	3000
Top		s	1.05	2.34	4.68	0.77	2.26	4.51	0.49	1.29	2.59	0.49	1.29	2.59	1.05	1.97	3.95
Bottom		s	1.45	3.20	6.41	1.05	3.09	6.19	0.67	1.77	3.54	0.67	1.77	3.54	1.44	2.71	5.41

			Transicoil BDC Motor - 05LH24				Transicoil BDC Motor - 05LM24				Transicoil BDC Motor - 05LL24			
Operating Speed	N_B	rpm	96400	60000	30000	3000	48220	38000	15000	3000	19400	16000	9700	3000
Top		s	0.14	0.23	0.45	4.51	0.28	0.36	0.90	4.51	0.70	0.75	1.40	4.51
Bottom		s	0.19	0.31	0.62	6.19	0.38	0.49	1.24	6.19	0.96	1.03	1.91	6.19

B.4.2 Force Generated at Finger Tip

Force Generated in Screw

				Degrees (°)
Pitch	p	mm	0.7	
Diameter	D	mm	4	
Number of Starts	n		1	
Lead	l		0.7	
Mean Thread Diameter	d_m	mm	3.545	
Root Diameter of screw	d_r	mm	3.141	
Major Diameter of screw	d_0	mm	4	
Thread Angle	θ	rad.	0.524	30
Coeff. Sliding Friction	f_s		0.112	(extremely good)
Nut Width	l	mm	6	
# Treads Engaged	n_t		8.6	
Depth of Thread	h	mm	0.429	
Thickness of Thread at Root Diameter	b	mm	0.175	
Mean Thrust Brg. Dia.	d_{mb}	mm	5.5	
Thrust Brg. Friction Coeff.				
- starting	f_b		0.006	
- running	f_b		*0.004*	
Helix Angle	α	rad.	0.063	3.60
Combined Angle	θ_n	rad.	0.523	29.95
Screw Efficiency				
-starting	η		31%	
- running	η		*32%*	



			Maxon Motor			Minimotor SA Motor			Minimotor SA Motor 2			Minimotor SA Motor 2			Minimotor SA Motor 3		
Motor Speed	N_B	rpm	stall	3000	6000	stall	3000	6000	stall	3000	6000	stall	3000	6000	stall	3000	6000
Raising Torque of Power Screw	T_G	Nmm	155.5	120.4	85.4	13.6	11.3	8.9	10.6	8.6	6.6	48.1	39.0	29.8	99.1	72.8	46.5
Weight Lifted (w/c. frict^n)	F	N	379.8	294.1	208.5	33.1	27.5	21.8	25.8	20.9	16.0	117.5	95.2	72.9	242.1	177.8	113.5
Weight Lifted	*F*	*N*	*452.8*	*350.7*	*248.5*	*39.5*	*32.8*	*26.0*	*30.8*	*24.9*	*19.1*	*140.1*	*113.5*	*86.9*	*288.6*	*212.0*	*135.4*
Bearing Stress (on Screw)	σ_B	N/mm^2	9.27	7.18	5.09	0.81	0.67	0.53	0.63	0.51	0.39	2.87	2.32	1.78	5.91	4.34	2.77
Bending Stress	σ_b	N/mm^2	167.20	129.49	91.77	14.59	12.10	9.62	11.36	9.20	7.05	51.73	41.91	32.08	106.58	78.28	49.99
Shearing Stress - screw	τ_{sc}	N/mm^2	38.49	29.81	21.13	3.36	2.79	2.21	2.61	2.12	1.62	11.91	9.65	7.39	24.53	18.02	11.51
- nut	τ_{nut}	N/mm^2	30.22	23.41	16.59	2.64	2.19	1.74	2.05	1.66	1.27	9.35	7.57	5.80	19.27	14.15	9.04

			Transicoil BDC Motor - 05LH24				Transicoil BDC Motor - 05LM24				Transicoil BDC Motor - 05LL24			
Motor Speed	N_B	rpm	stall	3000	30000	60000	stall	3000	15000	38000	stall	3000	9700	16000
Raising Torque of Power Screw	T_G	Nmm	842.8	816.5	580.5	318.2	429.4	402.7	295.9	91.0	176.3	149.0	88.1	12.7
Weight Lifted (w/c. frict^n)	F	N	2058.3	1994.3	1417.8	777.2	1048.9	983.6	722.6	222.3	430.5	363.9	215.2	31.1
Weight Lifted	*F*	*N*	*2453.9*	*2377.6*	*1690.3*	*926.6*	*1250.4*	*1172.6*	*861.5*	*265.0*	*513.2*	*433.9*	*256.6*	*37.0*
Bearing Stress (on Screw)	σ_B	N/mm^2	50.26	48.70	34.62	18.98	25.61	24.02	17.64	5.43	10.51	8.89	5.26	0.76
Bending Stress	σ_b	N/mm^2	906.15	877.95	624.16	342.16	461.75	433.02	318.11	97.87	189.52	160.21	94.76	13.68
Shearing Stress - screw	τ_{sc}	N/mm^2	208.59	202.10	143.68	78.76	106.29	99.68	73.23	22.53	43.63	36.88	21.81	3.15
- nut	τ_{nut}	N/mm^2	163.80	158.70	112.82	61.85	83.47	78.27	57.50	17.69	34.26	28.96	17.13	2.47

Force Transferred to Finger Tip

Radius Screw Force Acts at.	r	mm	15
Finger Length	L	mm	110

			Maxon Motor			Minimotor SA Motor			Minimotor SA Motor 2			Minimotor SA Motor 2			Minimotor SA Motor 3		
Force at Finger Tip	F_T	N	51.8	40.1	28.4	4.52	3.7	3.0	3.5	2.9	2.2	16.0	13.0	9.9	33.0	24.2	15.5

			Transicoil BDC Motor - 05LH24				Transicoil BDC Motor - 05LM24				Transicoil BDC Motor - 05LL24			
Force at Finger Tip	F_T	N	280.7	271.9	193.3	108.0	143.0	134.1	98.5	30.3	58.7	49.6	29.4	4.2

Appendix C : Stress Calculations

A quick calculation was made of the stress in the finger mounting lugs at the proximal end of the metacarpal blocks to ensure that these had sufficient cross-sectional area to withstand the maximum force exerted by the finger. To simplify the calculation it was assumed that the two lugs adjacent to the finger centre line did not take any of the load.

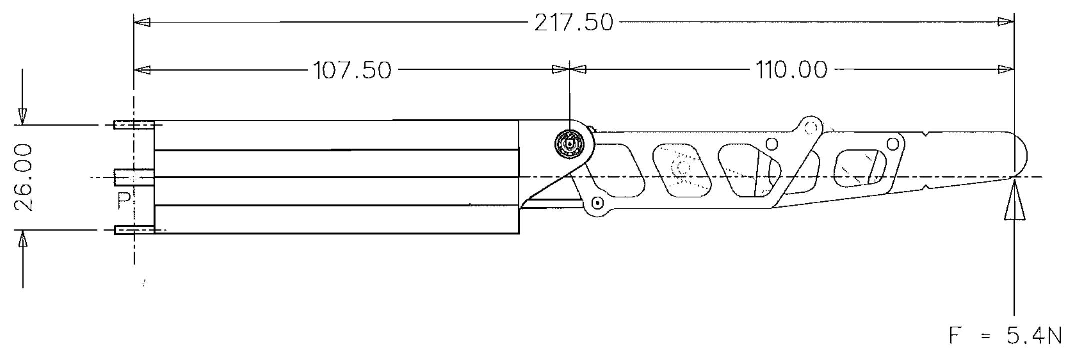


Figure C-1 *Maximum force applied at the finger tip*

Moment about point P due to load F (M_P):

$$M_p = F \times D$$

where:

F = loading applied at the finger tip = 5.4 N
D = the distance from the finger pivot that the load is acting at = 217.5 mm

$$\therefore M_p = 5.4 \times 217.5 \times 10^{-3}$$
$$= 1.1745\text{Nm}$$

Average shearing stress in finger hinge pin (τ_{ave}) due to motor load only:

$$\tau_{ave} = \frac{F}{A_{pin}}$$

where:

F = force applied at the mounting lug
A_{pin} = cross-sectional area of the pin

$$F = \frac{M_P}{2d}$$

where:

d = the distance from the centre line of the finger to the centre line of the mounting lug = 13 mm

$$\therefore F = \frac{1.175}{2(13 \times 10^{-3})}$$
$$= 45.17 \text{ N}$$

$$A_{pin} = \pi r^2$$

where:

r = radius of the mounting pin = 2.5 mm

$$\therefore A_{pin} = \pi (2.5)^2$$
$$= 19.64 \text{ mm}^2$$

$$\therefore \tau_{ave} = \frac{45.17}{19.64}$$
$$= 2.300 \text{ MPa}$$

So the maximum tensile stress in the mounting lug (σ_{lug}) can be calculated :

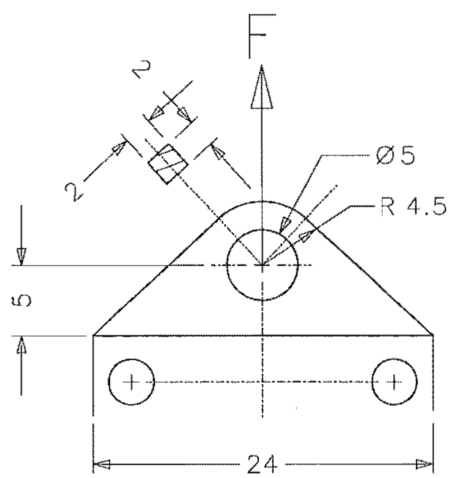


Figure C-2 *Top view of the mounting lug*

$$\sigma_{lug} = \frac{F_N}{A}$$

where:

F_N = the force acting on the lug at its thinnest point
A = cross-sectional area of the lug at its thinnest point = 4 mm²

$$2F = F_N \cos\alpha$$

$$\therefore F_N = \frac{F}{2\cos\alpha}$$

where:

α = the angle the force F_N is acting at = 47.13°

$$\therefore F_N = \frac{45.17}{2\cos(47.13)}$$
$$= 66.40\ \mathrm{N}$$

$$\therefore \sigma_{lug} = \frac{66.40}{4}$$
$$= 16.60\,\mathrm{MPa}$$

in each side of the lug.

The 2% Proof Stress of Aluminium is 55 MPa, so the stress in the mounting lug, σ_{lug}, is well within the maximum safe limit for the material.

Appendix D: Finger Tip Position Mapping

This appendix contains the MATLAB™ algorithms used to calculate finger tip position from the positions of the motor encoders and thus calculate the working range of the finger tip. Four modules are used:

- PLFIN96.M contains the input vectors for the movements of the two drive motors (in encoder counts), calls FIN6.M to calculate the resulting finger tip positions and plots the corresponding finger tip movement.
- FIN6.M contains the static parameters of the finger. It calls INTCRLE2.M to calculate the position of the proximal link, and again to calculate the position of the rocker in response to movements of the finger drive motors. This is then extrapolated to the finger tip, using INTCRLE2.M to calculate the position of each joint along the finger.
- INTCRLE2.M takes the centre positions, in x-y co-ordinates, and radii of n pairs of circles from FIN6.M in the form of a 6 × n matrix, and returns a 4 × n matrix containing the x and y positions of each of the two points of intersection for each pair of circles.
- INTCRLES.M, performs exactly the same operation as INTCRLE2.M but takes single pair of circles rather than a matrix containing n pairs of circles. This module is used to calculate the lengths of some of the finger links at the start of FIN6.M.

FILE: PLFIN96.M

```
% Sets input vectors for function fin6 and plots output
% ======================================================

% in this case, calculates the extent of the space accessible by the
% finger tip and displays it as a shaded area.
%                             Derek Ward
%                             5 March 1995

D1 = (0:200:12200)';          % Input vector for bottom lead screw
D2 = (0:110:8580)';           % Input vector for top lead screw
p = length(D1);
q = length(D2);
[x,y] = fin6(D1,0);
[u,v] = fin6(D1(p),D2);
[a,b] = fin6(D1,D2(q));
[c,d] = fin6(0,D2);
a = a(length(a):-1:1);
b = b(length(b):-1:1);
c = c(length(c):-1:1);
d = d(length(d):-1:1);
X = [x; u; a; c];
Y = [y; v; b; d];
fill(X,Y,'c'), grid
D1(p)
D2(q)
```

FILE: FIN6.M

```
function [x,y] = fin6(d1,d2)

% direct kinematics for finger - by Derek Ward
% (IDEAL MODEL)                    5 March 1995
%       d1 = encoder counts from home position on bottom motor
%       d2 = encoder counts from home position on top motor

% Finger parameters
% -----------------
pitch = 0.7;          % screw pitch (mm per rev.)
counts = 640;         % encoder counts per screw rev.

Phi = 65 * pi/180;      % Angle between CD and CE
Alpha = 158 * pi/180;   % Angle between CE and EF
Beta = 65 * pi/180;     % Angle between DG and GH
Gamma = 95.5 * pi/180;  % Angle between IE and EJ
Delta = 108 * pi/180;   % Angle between KJ and JL

xbo = -24.5;          % x offset of bottom nut home position from origin
yb = -15.0;           % offset of bottom screw from origin

xao = -24.5;          % x offset of top nut home position from origin
ya = -1.0;            % offset of top screw from origin

lce = 50;
lcd = 16.0;           % link length between pts O(C) and D
ldg = 16.0;           % link length between pts D and G
lgh = 25;
lef = 10.5;
lei = 13;
lej = 30;
ljk = 10;
ljl = 30;
lbd = (((lcd*cos(Phi)) - xbo)^2 + ((-lcd *sin(Phi)) - yb)^2)^.5 ;
lde = (lce^2 + lcd^2 - 2*lce*lcd*cos(Phi))^.5;
ldh = (ldg^2 + lgh^2 - 2*ldg*lgh*cos(Beta))^.5;
lcf = (lce^2 + lef^2 - 2*lce*lef*cos(Alpha))^.5;
lij = (lei^2 + lej^2 - 2*lei*lej*cos(Gamma))^.5;
lkl = (ljk^2 + ljl^2 - 2*ljk*ljl*cos(Delta))^.5;

Theta1 = pi/2 - Phi;       % Angle between CD and y axis
Theta2 = 16.6 * pi/180;    % Angle of rocker at start position
Theta3 = Gamma - pi/2;
Theta4 = Delta - pi/2;

copy0 = (zeros(size(d1)))';
Oxy = [copy0,copy0];       % Origin
Cxy = Oxy;

% Calculate Gxy at initial position (Finger straight)
Dxy0 = intcrles(Oxy(1),Oxy(2),xbo,yb,lcd,lbd);
Dxy0 = [Dxy0(1) Dxy0(2)];
Gxy0 = [Dxy0(1); Dxy0(2)] ...
        + [cos(Theta1) -sin(Theta1); sin(Theta1) cos(Theta1)] ...
        * [ldg * sin(Theta2); ldg * cos(Theta2)];

lag = ((Gxy0(1) - xao)^2 + (Gxy0(2) - ya)^2)^.5;

% Calculate link length between pts H and I
Exy0 = intcrles(Oxy(1), Oxy(2), Dxy0(1), Dxy0(2), lce, lde);
Exy0 = [Exy0(1) Exy0(2)];
Hxy0 = intcrles(Dxy0(1), Dxy0(2), Gxy0(1), Gxy0(2), ldh, lgh);
Hxy0 = [Hxy0(3) Hxy0(4)];
Ixy0 = [(-lei*sin(Theta3)) + Exy0(1) (-lei*cos(Theta3)) + Exy0(2)];
lhi = ((Ixy0(1) - Hxy0(1))^2 + (Ixy0(2) - Hxy0(2))^2)^.5;

% Calculate link length between pts F and K
Fxy0 = intcrles(Cxy(1), Cxy(2), Exy0(1), Exy0(2), lcf, lef);
Fxy0 = [Fxy0(1) Fxy0(2)];
Ixy0 = intcrles(Hxy0(1), Hxy0(2), Exy0(1), Exy0(2), lhi, lei);
Ixy0 = [Ixy0(3) Ixy0(4)];
Jxy0 = intcrles(Ixy0(1), Ixy0(2), Exy0(1), Exy0(2), lij, lej);
Jxy0 = [Jxy0(3) Jxy0(4)];
Kxy0 = [(-ljk*sin(Theta4)) + Jxy0(1) (-ljk*cos(Theta4)) + Jxy0(2)];
lfk = ((Kxy0(1) - Fxy0(1))^2 + (Kxy0(2) - Fxy0(2))^2)^.5;

% Solution - Bottom Screw
% -----------------------
xbm = d1/counts * pitch;   % distance nut moved from home position
xb = xbo - xbm;            % x position of nut rel. origin
```

```
copy1 = ones(size(d1));
% find point Bxy
Bxy = [xb yb(copy1)];

% find points Dxy
Dxy = intcrle2(Oxy,Bxy,lcd,lbd);
Dxy = Dxy(:,1:2);          % discard one point

% Solution - Top Screw
% --------------------
xam = d2/counts * pitch;   % distance nut moved from home position
xa = xao - xam;            % x position if nut rel. origin
copy2 = ones(size(d2));
% find point Axy
Axy = [xa ya(copy2)];

% find points Gxy
Gxy = intcrle2(Dxy,Axy,ldg,lag);
Gxy = Gxy(:,3:4);          % discard one point

% Extrapolating to the Finger Tip
% -------------------------------
% Given D, E can be found
Exy = intcrle2(Oxy, Dxy, lce, lde);
Exy = Exy(:,1:2);

% Given D & G, H can be found (using intcrle2)
Hxy = intcrle2(Dxy, Gxy, ldh, lgh);
Hxy = Hxy(:,3:4);

% Given H & E, use intersecting circles to find I
Ixy = intcrle2(Hxy, Exy, lhi, lei);
Ixy = Ixy(:,3:4);

% Given C & E, F can be found
Fxy = intcrle2(Cxy, Exy, lcf, lef);
Fxy = Fxy(:,1:2);

% Given E & I, J can be found
Jxy = intcrle2(Ixy, Exy, lij, lej);
Jxy = Jxy(:,3:4);

% Given F & J, K can be found
Kxy = intcrle2(Fxy, Jxy, lfk, ljk);
Kxy = Kxy(:,3:4);

% Given J & K, L (the finger tip position) can be calculated
Tipxy = intcrle2(Jxy, Kxy, ljl, lkl);
x = Tipxy(:,1);
y = Tipxy(:,2);
```

FILE: INTCRLE2.M

```
function  P = intcrle2(ca,cb,ka,kb)

cax = ca(:,1);
cay = ca(:,2);
cbx = cb(:,1);
cby = cb(:,2);

% Intersection of 2 planar circles
% eqn1 = |ra - ca| - ka    where ca is centre of circle, ka is radius of circle, ra is
                           position on circle
% eqn2 = |rb - cb| - kb    where cb is centre of circle, kb is radius of circle, ra is
                           position on circle

P(:,1) = (cax.^3 + cax.*cay.^2 - cax.^2.*cbx + cay.^2.*cbx - cax.*cbx.^2 + cbx.^3 ...
        - 2*cax.*cay.*cby - 2*cay.*cbx.*cby + cax.*cby.^2 + cbx.*cby.^2 - cax*ka.^2 +
        cbx*ka.^2 + cax*kb.^2 ...
        - cbx*kb.^2 + cay.*(cax.^2 + cay.^2 - 2*cax.*cbx + cbx.^2 - 2*cay.*cby + cby.^2 -
        ka.^2 + 2*ka*kb - kb.^2).^0.5 ...
        .*(-cax.^2 - cay.^2 + 2*cax.*cbx - cbx.^2 + 2*cay.*cby - cby.^2 + ka.^2 + 2*ka*kb +
        kb.^2).^0.5 ...
        - cby.*(cax.^2 + cay.^2 - 2*cax.*cbx + cbx.^2 - 2*cay.*cby + cby.^2 - ka.^2 + 2*ka*kb
        - kb.^2).^0.5 ...
        .*(-cax.^2 - cay.^2 + 2*cax.*cbx - cbx.^2 + 2*cay.*cby - cby.^2 + ka.^2 + 2*ka*kb +
        kb.^2).^0.5) ...
        ./ (2*(cax.^2 + cay.^2 - 2*cax.*cbx + cbx.^2 - 2*cay.*cby + cby.^2));
```

```
P(:,2) = (4*cay + 4*cby - 4*cay*ka^2./(cax.^2 + cay.^2 - 2*cax.*cbx + cbx.^2 - 2*cay.*cby +
         cby.^2) ...
         + 4*cby*ka^2./(cax.^2 + cay.^2 - 2*cax.*cbx + cbx.^2 - 2*cay.*cby + cby.^2) ...
         + 4*cay*kb^2./(cax.^2 + cay.^2 - 2*cax.*cbx + cbx.^2 - 2*cay.*cby + cby.^2) ...
         - 4*cby*kb^2./(cax.^2 + cay.^2 - 2*cax.*cbx + cbx.^2 - 2*cay.*cby + cby.^2) ...
         + 4*(-cax + cbx).*(cax.^2 + cay.^2 - 2*cax.*cbx + cbx.^2 - 2*cay.*cby + cby.^2 - ka^2
         + 2*ka*kb - kb^2).^0.5 ...
         .*(-cax.^2 - cay.^2 + 2*cax.*cbx - cbx.^2 + 2*cay.*cby - cby.^2 + ka^2 + 2*ka*kb +
         kb^2).^0.5 ...
         ./(cax.^2 + cay.^2 - 2*cax.*cbx + cbx.^2 - 2*cay.*cby + cby.^2))/8;

P(:,3) = (cax.^3 + cax.*cay.^2 - cax.^2.*cbx + cay.^2.*cbx - cax.*cbx.^2 + cbx.^3 ...
         - 2.*cax.*cay.*cby - 2.*cay.*cbx.*cby + cax.*cby.^2 + cbx.*cby.^2 - cax.*ka.^2 +
         cbx.*ka.^2 + cax.*kb.^2 ...  - cbx.*kb.^2 - cay.*(cax.^2 + cay.^2 - 2.*cax.*cbx +
         cbx.^2 - 2.*cay.*cby + cby.^2 - ka.^2 + 2.*ka.*kb - kb.^2).^0.5 ...
         .*(-cax.^2 - cay.^2 + 2.*cax.*cbx - cbx.^2 + 2.*cay.*cby - cby.^2 + ka.^2 + 2.*ka.*kb
         + kb.^2).^0.5 ...
         + cby.*(cax.^2 + cay.^2 - 2.*cax.*cbx + cbx.^2 - 2.*cay.*cby + cby.^2 - ka.^2 +
         2.*ka.*kb - kb.^2).^0.5 ...
         .*(-cax.^2 - cay.^2 + 2.*cax.*cbx - cbx.^2 + 2.*cay.*cby - cby.^2 + ka.^2 + 2.*ka.*kb
         + kb.^2).^0.5) ...
         ./ (2.*(cax.^2 + cay.^2 - 2.*cax.*cbx + cbx.^2 - 2.*cay.*cby + cby.^2));


P(:,4) = (4.*cay + 4.*cby - 4.*cay.*ka.^2./(cax.^2 + cay.^2 - 2.*cax.*cbx + cbx.^2 -
         2.*cay.*cby + cby.^2) ...
         + 4.*cby.*ka.^2./(cax.^2 + cay.^2 - 2.*cax.*cbx + cbx.^2 - 2.*cay.*cby + cby.^2) ...
         + 4.*cay.*kb.^2./(cax.^2 + cay.^2 - 2.*cax.*cbx + cbx.^2 - 2.*cay.*cby + cby.^2) ...
         - 4.*cby.*kb.^2./(cax.^2 + cay.^2 - 2.*cax.*cbx + cbx.^2 - 2.*cay.*cby + cby.^2) ...
         + 4.*(cax - cbx).*(cax.^2 + cay.^2 - 2.*cax.*cbx + cbx.^2 - 2.*cay.*cby + cby.^2 -
         ka.^2 + 2.*ka.*kb - kb.^2).^0.5 ...
         .*(-cax.^2 - cay.^2 + 2.*cax.*cbx - cbx.^2 + 2.*cay.*cby - cby.^2 + ka.^2 + 2.*ka.*kb
         + kb.^2).^0.5 ...
         ./  (cax.^2 + cay.^2 - 2.*cax.*cbx + cbx.^2 - 2.*cay.*cby + cby.^2))/8;
```

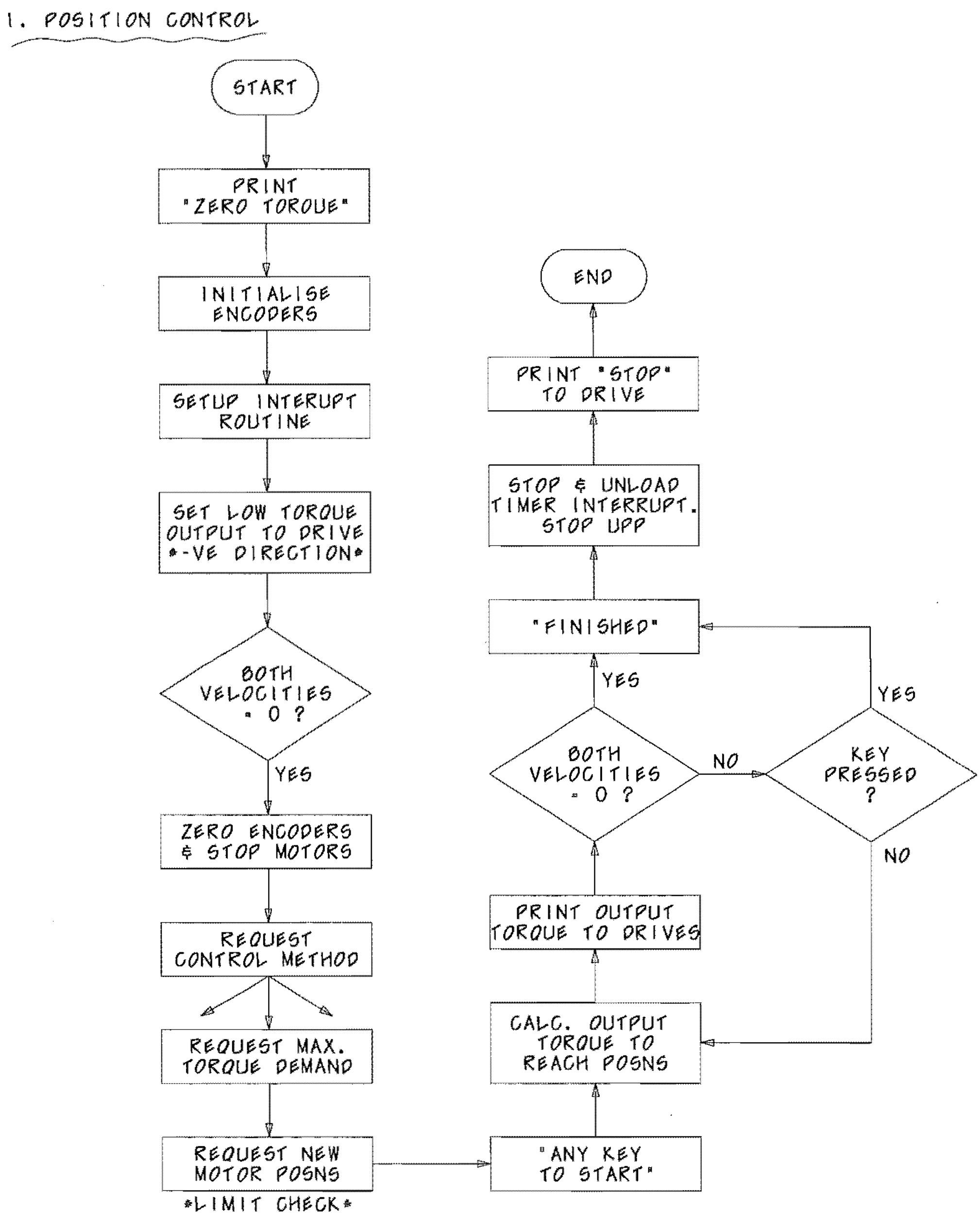
FILE: INTCRLES.M

```
function  P = intcrles(Cax,Cay,Cbx,Cby,Ka,Kb)

% Intersection of 2 planar circles
% eqn1 = |Ra - Ca| - Ka    where Ca is centre of circle, Ka is radius of circle, Ra is
                           position on circle
% eqn2 = |Rb - Cb| - Kb    where Cb is centre of circle, Kb is radius of circle, Ra is
                           position on circle

P(1) = (Cax^3 + Cax*Cay^2 - Cax^2*Cbx + Cay^2*Cbx - Cax*Cbx^2 + Cbx^3 - 2*Cax*Cay*Cby -
       2*Cay*Cbx*Cby + Cax*Cby^2 + Cbx*Cby^2 - Cax*Ka^2 + Cbx*Ka^2 + Cax*Kb^2- Cbx*Kb^2 +
       Cay*(Cax^2 + Cay^2 - 2*Cax*Cbx + Cbx^2 - 2*Cay*Cby + Cby^2 - Ka^2 + 2*Ka*Kb - Kb^2)^0.5
       *(-Cax^2 - Cay^2 + 2*Cax*Cbx - Cbx^2 + 2*Cay*Cby - Cby^2 + Ka^2 + 2*Ka*Kb + Kb^2)^0.5 -
       Cby*(Cax^2 + Cay^2 - 2*Cax*Cbx + Cbx^2 - 2*Cay*Cby + Cby^2 - Ka^2 + 2*Ka*Kb - Kb^2)^0.5
       *(-Cax^2 - Cay^2 + 2*Cax*Cbx - Cbx^2 + 2*Cay*Cby - Cby^2 + Ka^2 + 2*Ka*Kb + Kb^2)^0.5)
       / (2*(Cax^2 + Cay^2 - 2*Cax*Cbx + Cbx^2 - 2*Cay*Cby + Cby^2));

P(2) = (4*Cay + 4*Cby - 4*Cay*Ka^2/(Cax^2 + Cay^2 - 2*Cax*Cbx + Cbx^2 - 2*Cay*Cby + Cby^2)+
       4*Cby*Ka^2/(Cax^2 + Cay^2 - 2*Cax*Cbx + Cbx^2 - 2*Cay*Cby + Cby^2) ...
       + 4*Cay*Kb^2/(Cax^2 + Cay^2 - 2*Cax*Cbx + Cbx^2 - 2*Cay*Cby + Cby^2) ...
       - 4*Cby*Kb^2/(Cax^2 + Cay^2 - 2*Cax*Cbx + Cbx^2 - 2*Cay*Cby + Cby^2) ...
       + 4*(-Cax + Cbx)*(Cax^2 + Cay^2 - 2*Cax*Cbx + Cbx^2 - 2*Cay*Cby + Cby^2 - Ka^2 +
       2*Ka*Kb - Kb^2)^0.5 *(-Cax^2 - Cay^2 + 2*Cax*Cbx - Cbx^2 + 2*Cay*Cby - Cby^2 + Ka^2 +
       2*Ka*Kb + Kb^2)^0.5 / (Cax^2 + Cay^2 - 2*Cax*Cbx + Cbx^2 - 2*Cay*Cby + Cby^2))/8;

P(3) = (Cax^3 + Cax*Cay^2 - Cax^2*Cbx + Cay^2*Cbx - Cax*Cbx^2 + Cbx^3 - 2*Cax*Cay*Cby -
       2*Cay*Cbx*Cby + Cax*Cby^2 + Cbx*Cby^2 - Cax*Ka^2 + Cbx*Ka^2 + Cax*Kb^2 - Cbx*Kb^2 -
       Cay*(Cax^2 + Cay^2 - 2*Cax*Cbx + Cbx^2 - 2*Cay*Cby + Cby^2 - Ka^2 + 2*Ka*Kb - Kb^2)^0.5
       *(-Cax^2 - Cay^2 + 2*Cax*Cbx - Cbx^2 + 2*Cay*Cby - Cby^2 + Ka^2 + 2*Ka*Kb + Kb^2)^0.5 +
       Cby*(Cax^2 + Cay^2 - 2*Cax*Cbx + Cbx^2 - 2*Cay*Cby + Cby^2 - Ka^2 + 2*Ka*Kb - Kb^2)^0.5
       *(-Cax^2 - Cay^2 + 2*Cax*Cbx - Cbx^2 + 2*Cay*Cby - Cby^2 + Ka^2 + 2*Ka*Kb + Kb^2)^0.5)
       / (2*(Cax^2 + Cay^2 - 2*Cax*Cbx + Cbx^2 - 2*Cay*Cby + Cby^2));


P(4) = (4*Cay + 4*Cby - 4*Cay*Ka^2/(Cax^2 + Cay^2 - 2*Cax*Cbx + Cbx^2 - 2*Cay*Cby + Cby^2)+
       4*Cby*Ka^2/(Cax^2 + Cay^2 - 2*Cax*Cbx + Cbx^2 - 2*Cay*Cby + Cby^2) ...
       + 4*Cay*Kb^2/(Cax^2 + Cay^2 - 2*Cax*Cbx + Cbx^2 - 2*Cay*Cby + Cby^2) ...
       - 4*Cby*Kb^2/(Cax^2 + Cay^2 - 2*Cax*Cbx + Cbx^2 - 2*Cay*Cby + Cby^2) ...
       + 4*(Cax - Cbx)*(Cax^2 + Cay^2 - 2*Cax*Cbx + Cbx^2 - 2*Cay*Cby + Cby^2 - Ka^2 + 2*Ka*Kb
       - Kb^2)^0.5 ...
       *(-Cax^2 - Cay^2 + 2*Cax*Cbx - Cbx^2 + 2*Cay*Cby - Cby^2 + Ka^2 + 2*Ka*Kb + Kb^2)^0.5
       ...
       / (Cax^2 + Cay^2 - 2*Cax*Cbx + Cbx^2 - 2*Cay*Cby + Cby^2))/8;
```

Appendix E: Finger Control

A simple closed loop position control program was designed for the Canterbury finger. This was then implemented using Borland C++ v3.0 [Borland International, Inc.]. The following two sections contain a flow diagram of the control program, and a listing of the C++ code.

E.1 Finger Control Flow Diagram



E.2 C++ Control Program

Finger control code written and compiled using Borland C++ v3.0 [Borland International, Inc.].

```
/* *****************************************************************
   File      : FINCTRL2.C
   Author    : Derek Ward
   Date      : 11/4/96
   Version   : 1.0

Copyright (C) 1996 Derek Ward & University of Canterbury
***************************************************************** */

#include <stdio.h>
#include <stdlib.h>
#include <conio.h>
#include <stdarg.h>
#include <ctype.h>
#include <dos.h>
#include "pwm.h"

/* #define MAXUINT 0xFFFF */
#define NUM_ENCODERS 2

#define VERYSMALL .00001       /* velocity that is == stopped */
#define INT_PERIOD 600         /* how often for UPP to create interrupts */
#define INT_STEP 3.25          /* Step size in microsec of interrupt period */
#define LOW_TORQUE 50

#define NEG_LIM 0              /* Limit of travel in -ve direction */
#define POS_LIM0 12700         /* Max. travel for Encoder0 (bottom motor) */
#define POS_LIM1 8700          /* Max. travel for Encoder1 (top motor) */
#define STOP 128               /* Torque output to drive that is == motor stopped */
#define MAX_TORQUE 127         /* Max. torque demand user can request */
#define POS_GAIN .8
#define MIN_ERROR 10

#define LPT1 0x378
#define DATA_PORT LPT1
#define ADDR_PORT (DATA_PORT+2)
#define MOTOR_A 0x0A           /* Address 00 */
#define MOTOR_B 0x08           /* Address 01 */
#define MOTOR_C 0x02           /* Address 02 */
#define MOTOR_D 0x00           /* Address 03 */

#define TRUE    1
#define FALSE   0

#ifndef __LARGE__
#error Use large memory model for UPP stuff!!!
#endif

#define NoCon   0
#define Prop    1
#define Vel     2
#define Torq    3

int   IntFlag;

int   EncoderPos0, EncoderPos1;
float   Velocity0, Velocity1;

int   TorqueOut0, TorqueOut1;
int   PosError0=MIN_ERROR, PosError1=MIN_ERROR;
int   ReqPos0=0, ReqPos1=0;
int   MaxTorque;

int   Count=0;


/*   ---------------------------------------------------------------
   ErrorMessage(char Format[], ...)
   Calls fprintf to stderr and exits.
   --------------------------------------------------------------- */
void  ErrorMessage(const char Format[], ...)
{
   va_list ArgPtr;

   va_start(ArgPtr, Format);
```

```
   vfprintf(stderr, Format, ArgPtr);
   va_end(ArgPtr);
   exit(1);
}

/* ---------------------------------------------------------------------
   KeyWait()
   Prints "Press a key..." and waits for a key.
   --------------------------------------------------------------------- */
void   KeyWait(void)
{
   printf("Press a key...");
   getch();
   printf("\n");
}

/* ---------------------------------------------------------------------
   CalcTorque()
   --------------------------------------------------------------------- */
int   CalcTorque(int PosnError, int Max)
{
   int TorqueOut;

   if (PosnError<0)
      TorqueOut=127+(int)(POS_GAIN*(float)PosnError);
   else
      TorqueOut=(int)(POS_GAIN*(float)PosnError)+128;

   if (TorqueOut>(Max+128))        /* Restricts TorqueOut to maximum value */
      TorqueOut=(Max+128);         /* specified by user. */
   else if (TorqueOut<(127-Max))
      TorqueOut=(127-Max);

   return TorqueOut;
}


/*----------------------------------------------------------------------
   NumToPort(Torque, Address)
      Sends the required output torque demand to the appropriate motor
      address.
------------------------------------------------------------------------ */
void   NumToPort(unsigned int Torque, char Address)
{
   outp(DATA_PORT, Torque);
   delay(0);
   outp(ADDR_PORT, Address);
   delay(0);
   outp(ADDR_PORT, Address+1);
   delay(0);
   outp(ADDR_PORT, Address);
}


/* ---------------------------------------------------------------------
   When interrupted by UPP, read encoders and calculate motor velocities
   --------------------------------------------------------------------- */
void   InterruptHandler(void)
{
   int   OldEncoderPos0, OldEncoderPos1;

   Count++;

   OldEncoderPos0 = EncoderPos0;
   OldEncoderPos1 = EncoderPos1;
   EncoderPos0 = ReadSingleEncoder(0);
   EncoderPos1 = ReadSingleEncoder(1);

   /* Calculate velocity in counts/microsecond */
   Velocity0 = (OldEncoderPos0 - EncoderPos0)/(INT_STEP * INT_PERIOD);
   Velocity1 = (OldEncoderPos1 - EncoderPos1)/(INT_STEP * INT_PERIOD);


   PosError0=ReqPos0-EncoderPos0;
   PosError1=ReqPos1-EncoderPos1;
   if (IntFlag==Prop)
   {
      TorqueOut0=CalcTorque(PosError0, MaxTorque);
      TorqueOut1=CalcTorque(PosError1, MaxTorque);

      NumToPort(TorqueOut0, MOTOR_A);
      NumToPort(TorqueOut1, MOTOR_B);
   }
}
```

```
/* -----------------------------------------------------------------
   Find -ve limit of motor travel & set encoders to zero at this point.
   (i.e. when finger is straight)
   ----------------------------------------------------------------- */
void   SetupMotors(void)          /* read all encoders simultaneously */
{
   NumToPort(LOW_TORQUE, MOTOR_A);      /* Set low torque (-ve Dirn) */
   NumToPort(LOW_TORQUE, MOTOR_B);      /* Set low torque (-ve Dirn) */

   delay(100);
   while(Velocity0 > VERYSMALL || Velocity1 > VERYSMALL);

   SetEncoder(0, NEG_LIM);
   printf("Encoder 0 zeroed\n");

   SetEncoder(1, NEG_LIM);
   printf("Encoder 1 zeroed\n");

   NumToPort(STOP, MOTOR_A);
   NumToPort(STOP, MOTOR_B);
}

/* -----------------------------------------------------------------
   Initialise()

-------------------------------------------------------------------- */
void   Initialise(void)
{
   int   NumEncoders;

   NumToPort(STOP, MOTOR_A);
   NumToPort(STOP, MOTOR_B);
   NumToPort(STOP, MOTOR_C);
   NumToPort(STOP, MOTOR_D);

   NumEncoders = InstallEncoder(NUM_ENCODERS);
   if (NumEncoders!=NUM_ENCODERS)
      ErrorMessage("InstallEncoder(%d) failed to install %d encoders.",
         NUM_ENCODERS, NUM_ENCODERS);
   else
      printf("%d encoders installed.\n", NumEncoders);
   KeyWait();

   /* Create an interrupt from the UPP every IntPeriod x 3.25 microsec */

   InstallTimerInt(InterruptHandler);
   StartTimerInt(INT_PERIOD);

   SetupMotors();
}


/* StartScreen()----------------------------------------------------
      Print startup screen, and if key pressed is within range, return
      the value of that key.
   ----------------------------------------------------------------- */
int   StartScreen(void)
{
   int   Key;

   do {
      printf("What type of motor control would you like to use ?\n");
      printf("   Torque   : press <T>\n");
      printf("   Position : press <P>\n");
      printf("   Velocity : press <V>\n");

      Key=toupper(getch());
      } while (Key!='T' && Key!='P' && Key!='V' && printf("Wrong. Try again.\n\n"));
   return Key;
}


/* -----------------------------------------------------------------
   ReadInt(min, max)

   Read value typed and if it is within the range specified by min &
   max, return that value.
-------------------------------------------------------------------- */
int   ReadInt(int min, int max)
{
   int   val;
```

```
   do   {
      scanf("%d", &val);
   } while(!((val>=min && val<=max) || !printf("Wrong. Range is %d to %d.\n", min, max)));

   return val ;
}


/* -----------------------------------------------------------------------
   OutTorque()\
      Sends torques calculated in the interrupt routine to the printer
      port, while the position error is still large.
------------------------------------------------------------------------ */
void   OutputTorque(void)
{
   int EXIT;
   IntFlag=Prop;
   EXIT = FALSE;
   do {
      printf("PosError0  =%6d, PosError1  =%6d ", PosError0, PosError1);
      printf("EncoderPos0=%6d, EncoderPos1=%6d\n", EncoderPos0, EncoderPos1);
      printf("TorqueOut0 =%6d, TorqueOut1 =%6d ", TorqueOut0, TorqueOut1);
      printf("Velocity0  =%6g, Velocity1  =%6g\n\n", Velocity0, Velocity1);

      if (kbhit())
      {
         EXIT = TRUE;
         printf("key pressed");
      }

      if (abs(PosError0)<MIN_ERROR && abs(PosError1)<MIN_ERROR )
      {
         EXIT = TRUE;
      }
   }while (EXIT == FALSE);
   IntFlag=NoCon;
}


/* PositionControl()------------------------------------------------------

------------------------------------------------------------------------ */
void   PositionControl(void)
{
   printf("Enter Maximum torque (0-%d): \n", MAX_TORQUE);
   MaxTorque=ReadInt(0,MAX_TORQUE);
   printf("Enter new position of motor #1 (0-%d)\n",POS_LIM0);
   ReqPos0=ReadInt(0,POS_LIM0);

   printf("Enter new position of motor #2 (0-%d)\n",POS_LIM1);
   ReqPos1=ReadInt(0,POS_LIM1);

   printf("  Press any key to start motors\n");
   getch();


   OutputTorque();
}


/* ---------------------------------------------------------------------
   main()
   --------------------------------------------------------------------- */
void   main(void)
{
   Initialise();

   TorqueOut0=STOP;
   TorqueOut1=STOP;

   switch(StartScreen())
   {
      case 'T' : break;
      case 'P' : PositionControl(); break;
      case 'V' : break;
      default: printf("Wrong! Try again.%c", 0x07);
   }

   printf("Move Finished\n");

   RemoveTimerInt();

   StopTimerInt();
   StopUpp();
```

```
    NumToPort(STOP, MOTOR_A);
    NumToPort(STOP, MOTOR_B);
    NumToPort(STOP, MOTOR_C);
    NumToPort(STOP, MOTOR_D);
}
```

E.3 Header File for UPP Card Control Library

```
/*
PWM.H
gives up to 8 channels of pwm output, at a clock rate of 3.25us and up to 8 channels of
incremental encoder input.  Up to 8 input and 8 output pins can be used depending on the
number of PWM and encoder channels.  An interrupt handler can be installed to call a function
at set time intervals
*/
/*              PWM Pin Assignment
                ------------------

    PWM Channel      PWM Output          Direction (Type 1)
       0               U0  (20)            U1  (2)       (39 pin D plug pin number)
       1               U2  (21)            U3  (3)
       2               U4  (22)            U5  (4)
       3               U6  (23)            U7  (5)
       4               U14 (27)            U15 (9)
       5               U12 (26)            U13 (8)
       6               U10 (25)            U11 (7)
       7               U8  (24)            U9  (6)
                  All pins are on UPP 2


                Output Pin Assignment
                ---------------------
                       <=4 pwm    5 pwm     6 pwm     7 pwm     8 pwm
    Output number       pin        pin       pin       pin       pin
        0             U8  (24)  U8  (24)  U8  (24)  U8 (24)      -
        1             U9  (6)   U9  (6)   U9  (6)   U9 (6)       -
        2             U10 (25)  U10 (25)  U10 (25)    -          -
        3             U11 (7)   U11 (7)   U11 (7)     -          -
        4             U12 (26)  U12 (26)    -         -          -
        5             U13 (8)   U13 (8)     -         -          -
        6             U14 (27)    -         -         -          -
        7             U15 (9)     -         -         -          -
                  All Pins are on UPP 2


                Encoder Pin Assignment
                ----------------------

    Encoder Channel          Input pin 1     Input pin 2
       0                        U0  (28)        U1  (10)
       1                        U2  (29)        U3  (11)
       2                        U4  (30)        U5  (12)
       3                        U6  (31)        U7  (13)
       4                        U14 (35)        U15 (17)
       5                        U12 (34)        U13 (16)
       6                        U10 (33)        U11 (15)
       7                        U8  (32)        U9  (14)
                  All Pins are on UPP 1


                Input Pin Assignment
                --------------------

               <4 encoders  5 encoders  6 encoders  7 encoders  8 encoders
    Input Number   Pin         Pin         Pin         Pin         Pin
        0       U8  (32)    U8  (32)    U8  (32)    U8  (32)        -
        1       U9  (14)    U9  (14)    U9  (14)    U9  (14)        -
        2       U10 (33)    U10 (33)    U10 (33)       -            -
        3       U11 (15)    U11 (15)    U11 (15)       -            -
        4       U12 (34)    U12 (34)       -           -            -
        5       U13 (16)    U13 (16)       -           -            -
        6       U14 (35)       -           -           -            -
        7       U15 (17)       -           -           -            -
                  All Pins on UPP 1


*/

#define UINT unsigned int

int InstallPWMControl(int NumPWMChannels, int NumPWMSteps,int PWMType[]);
/* Sets up the required number of PWM channels.
      int PWMType[NumPWMChannels] gives the type for each channel
      Type 1
```

```
         Each channel has 1 PWM and 1 direction with PWM initialised to zero
      Type 2
         Each channel has 1 PWM output with 0% duty cycle as zero
      Type 3
         Each channel has 1 PWM output with 50% duty cycle as zero

      Each PWM step takes 3.25us.
      Frequency of PWM is determined by NumPWMSteps
            1000 steps = 307 Hz
             200 steps = 1538 Hz.
      Returns the number of channels initialised.
*/


void SetSinglePWMValue(unsigned int Channel, int PWMValue);
/* As for SetPWMValues but only for indicated channel
*/


int SetPWMValues(int PWMArray[]);
/* int PWMArray[NumPWMChannels]
   If PWMArray[i] is negative, direction output is set high
   else output is set low.
   PWM is checked to make sure it is <= NumPWMSteps
   and is adjusted to this effect.
   returns 1 if Ok
*/

UINT InstallEncoder(UINT NumEncodeChannels);
/* Sets UPP up to read up to 8 quadrature encoders.
   The counters are set to zero.
   Returns number of channels installed.
*/

int SetEncoder(UINT channel, UINT Value);
/*  Sets encoder counter to value specified.
    returns 0 if error.
*/

void ReadEncoders(int Position[]);
/* int Position[ArrayEncodeChannels]
   Reads all encoders
*/

UINT ReadSingleEncoder(UINT channel);
/* reads single encoder channel and returns its value
   returns max UINT if not valid channel
*/

void StopUpp(void);
/* Turns off UPP when Finished.
*/
void InstallTimerInt(void (*Func)(void));
/* Must be followed by StartTimerInt to set the period and start operation.
   Calls Func at time intervals specified by Period in 3.25 micro second steps
   The maximum time is 212 ms.
   Calls function void Func(void) defined by user. This function is called
   inside an interrupt and so should be as short as possible.
   All sub functions called by this function should be exclusively for its
   use and it should      not make any dos calls as dos is not re-entrant.
*/

void StartTimerInt(unsigned int Period);
/* Enables the timer interrupt, installing a new period as above.
*/


void StopTimerInt(void);
/* Disables timer interrupt but leaves installed
*/


void RemoveTimerInt(void);
/* disables timer interrupt
*/

int InstallInputs(int NumInputs);
/* The maximum number of inputs is 8 but this is reduced
   as the number of encoder channels increases.
   Returns number of inputs installed.
*/

int ReadInputs(void);
/*
```

```
   Return value is
            bit 0 = input 0
            bit 7 = input 7
*/

int InstallOutputs(int NumOutputs);
/* The maximum number of outputs is 8 but this is reduced
   as the number of PWM channels increases.
   Returns the number of outputs installed.
*/

void WriteOutput(UINT Value);
/* bit 0 = output 0
   bit 7 = output 7
*/

UINT ReadOutput(void);
/* read back data sent to output
*/
```

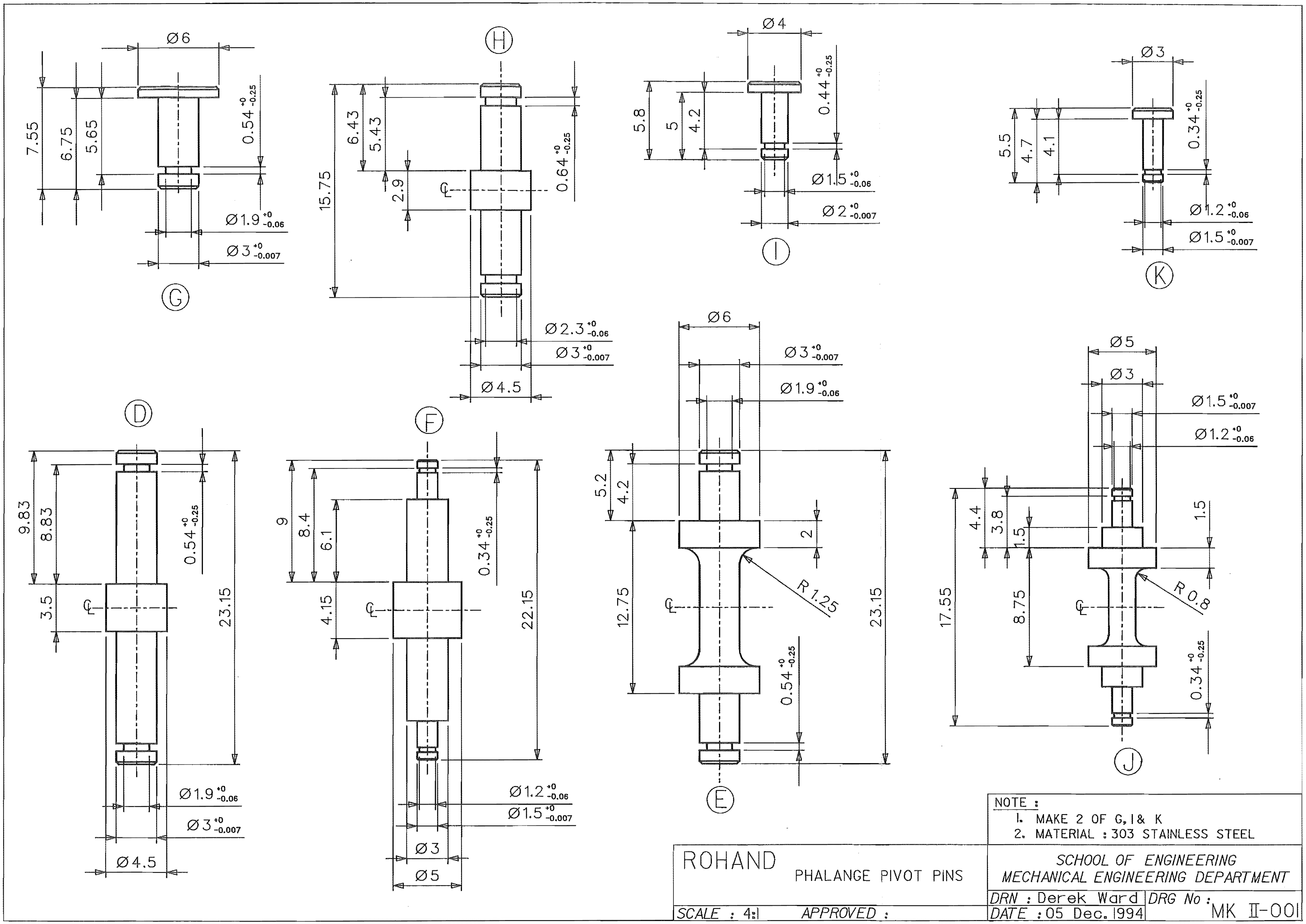
Appendix F: Drawings

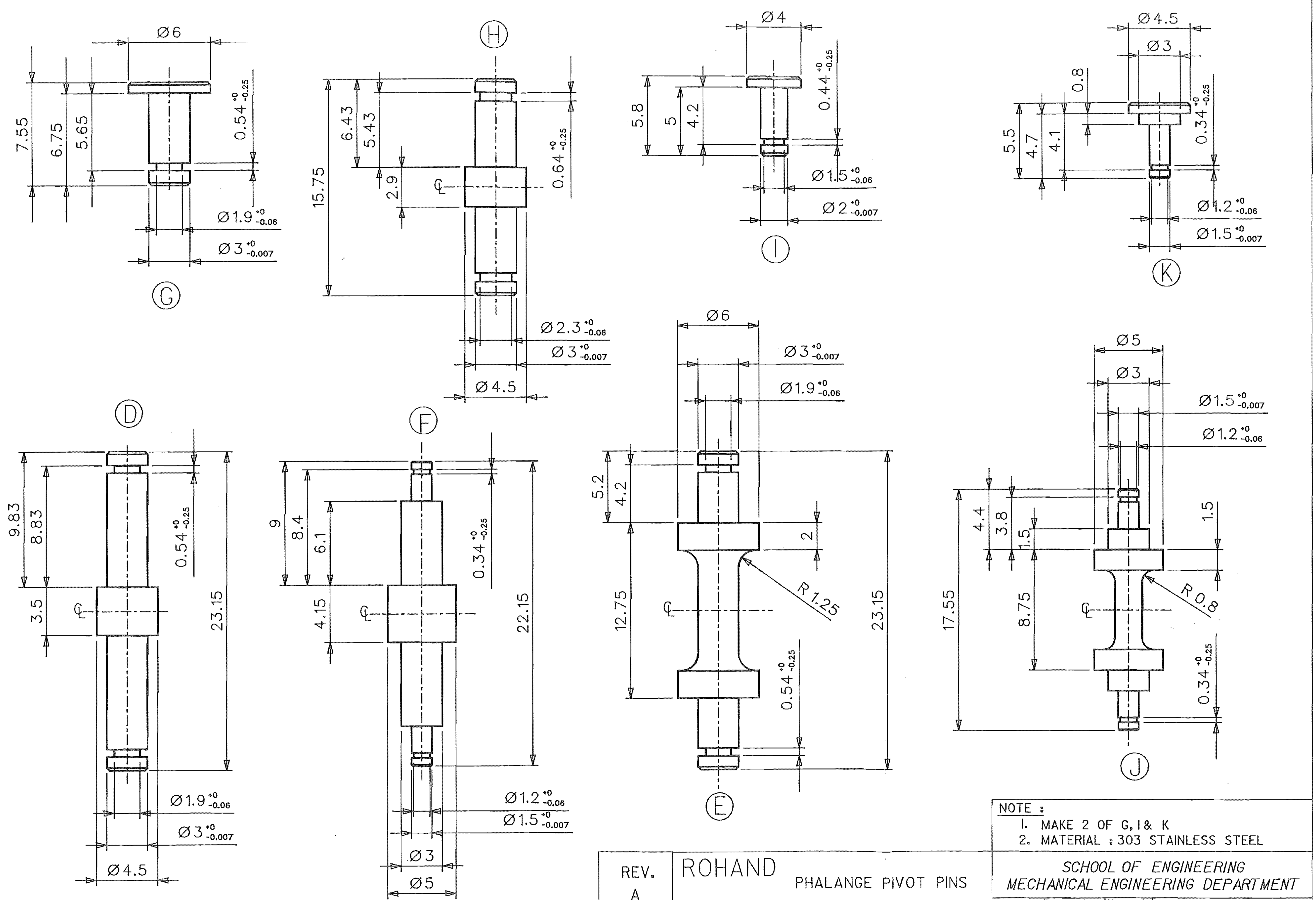
This appendix contains the manufacturing drawings for the Canterbury finger. The drawings are listed in table F-1.

Table F-1 *Manufacturing Drawings for the Canterbury Finger.*

Number	Rev.		Date	Size	Notes
MKII - 001		Phalange Pivot Pins	12 May. 1994	A3	
-001	A	Phalange Pivot Pins	5 Nov. 1995	A3	Drg. 001 with modified pins included
- 002		Phalange Spacers	12 May. 1994	A3	
-002	A	Phalange Spacers	5 Nov. 1995	A3	Drg. 002 with modified spacers included
- 003		Modified Phalange Pin & Spacers	11 May. 1995	A4	Modification of 001 & 002 because of incorrectly manufactured plates.
- 004		Carpal Body Block	31 Aug. 1995	A3	
- 005		Main Drive Screw	29 Aug. 1995	A4	
- 006		Flexible Coupling	11 Aug. 1995	A4	
- 007		Drive Nut & Pins	30 Aug. 1995	A4	
- 008		Phalange Support Bracket	29 Aug. 1995	A3	
- 009		Driveline Spacers	31 Aug. 1995	A4	
- 010		Assembly Drawing	31 Aug. 1995	A3	Shows assembly of power pack only

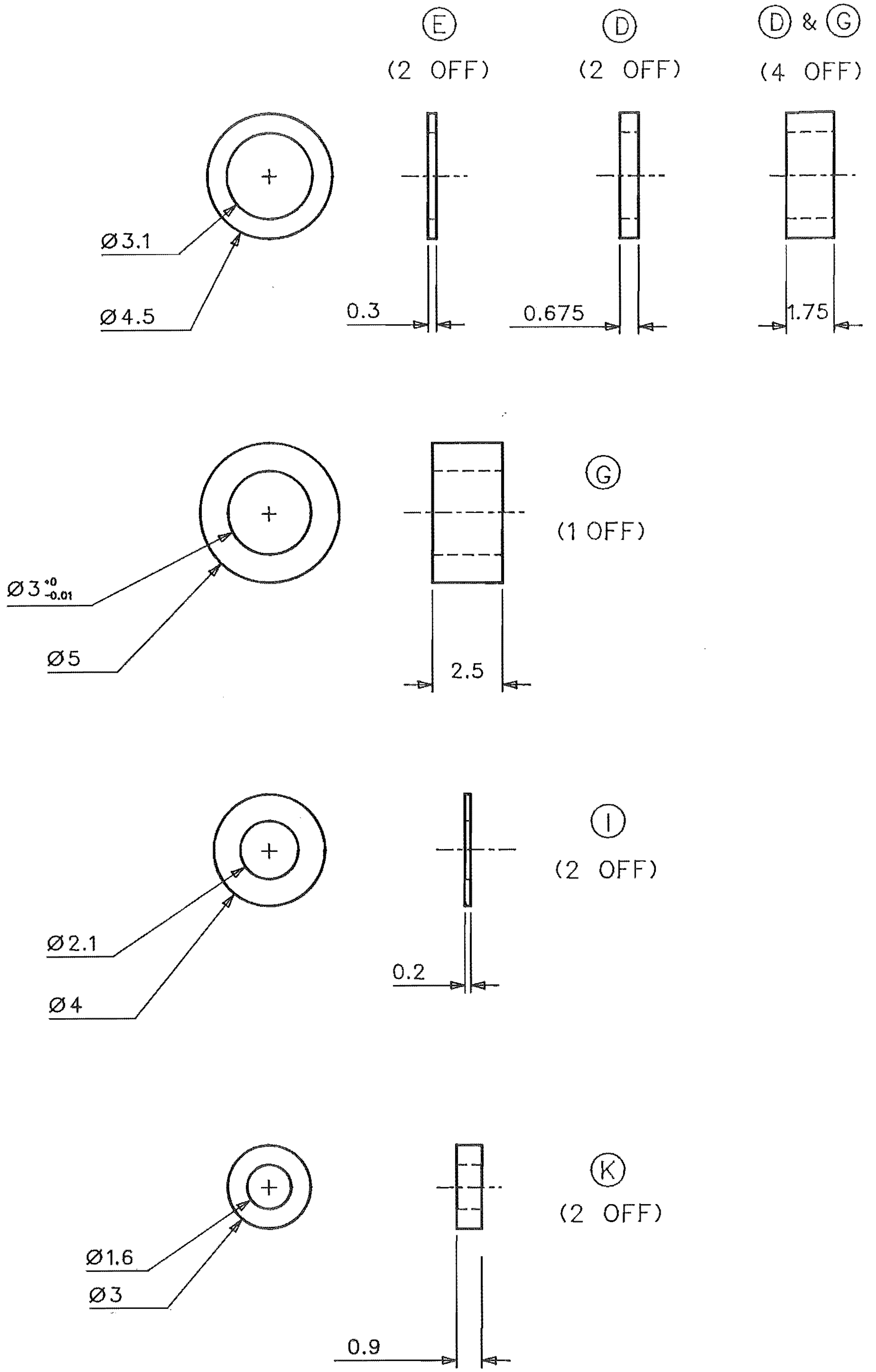
A more complete listing that includes lists of files and reference files is included at the end of this appendix, as are rendered images of the finger taken from MicroStation®. No working drawings were made for the phalange plates since the design for these was transferred directly to the CNC milling machine using Mastercam®, but a drawing of their basic dimensions, and another of the plates as laid out for the CNC mill are included.


G
Ø6
7.55
6.75
5.65
0.54 +0 -0.25
Ø1.9 +0 -0.06
Ø3 +0 -0.007
H
15.75
6.43
5.43
2.9
0.64 +0 -0.25
Ø2.3 +0 -0.06
Ø3 +0 -0.007
Ø4.5
I
Ø4
5.8
5
4.2
0.44 +0 -0.25
Ø1.5 +0 -0.06
Ø2 +0 -0.007
K
Ø3
5.5
4.7
4.1
0.34 +0 -0.25
Ø1.2 +0 -0.06
Ø1.5 +0 -0.007
D
9.83
8.83
3.5
0.54 +0 -0.25
23.15
Ø1.9 +0 -0.06
Ø3 +0 -0.007
Ø4.5
F
9
8.4
6.1
4.15
0.34 +0 -0.25
22.15
Ø1.2 +0 -0.06
Ø1.5 +0 -0.007
Ø3
Ø5
E
Ø6
Ø3 +0 -0.007
Ø1.9 +0 -0.06
5.2
4.2
2
R 1.25
12.75
23.15
0.54 +0 -0.25
J
Ø5
Ø3
Ø1.5 +0 -0.007
Ø1.2 +0 -0.06
4.4
3.8
1.5
1.5
R 0.8
17.55
8.75
0.34 +0 -0.25
NOTE :
1. MAKE 2 OF G, I & K
2. MATERIAL : 303 STAINLESS STEEL
ROHAND
PHALANGE PIVOT PINS
SCHOOL OF ENGINEERING
MECHANICAL ENGINEERING DEPARTMENT
DRN : Derek Ward
DATE : 05 Dec. 1994
DRG No : MK II-001
SCALE : 4:1
APPROVED :

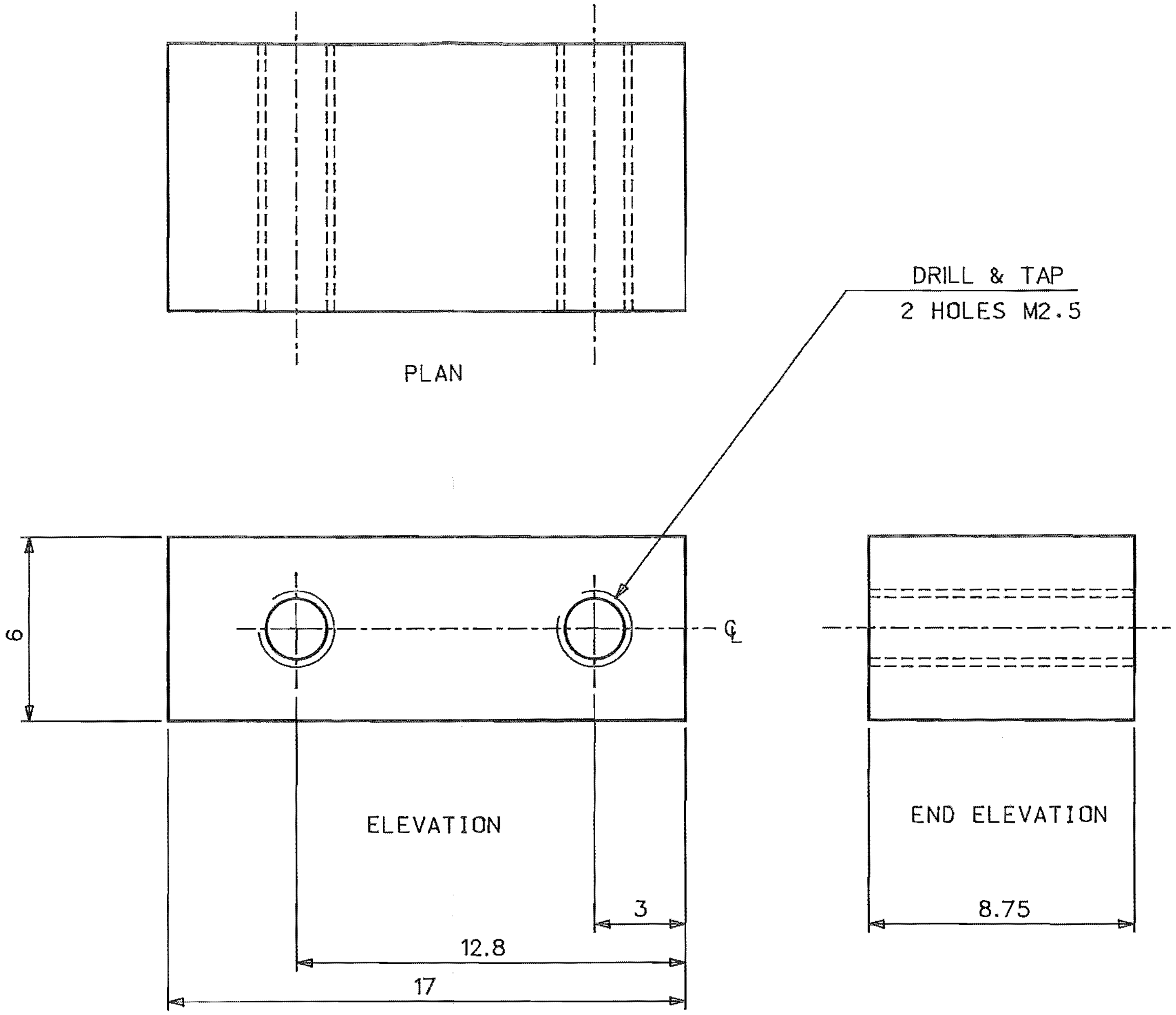


NOTE :
1. MAKE 2 OF G, I & K
2. MATERIAL : 303 STAINLESS STEEL

REV. A	ROHAND PHALANGE PIVOT PINS	SCHOOL OF ENGINEERING MECHANICAL ENGINEERING DEPARTMENT
	SCALE : 4:1 APPROVED :	DRN : Derek Ward DATE : 11 May 1995
		DRG No : MK II-001



1. PHALANGE SPACER WASHERS

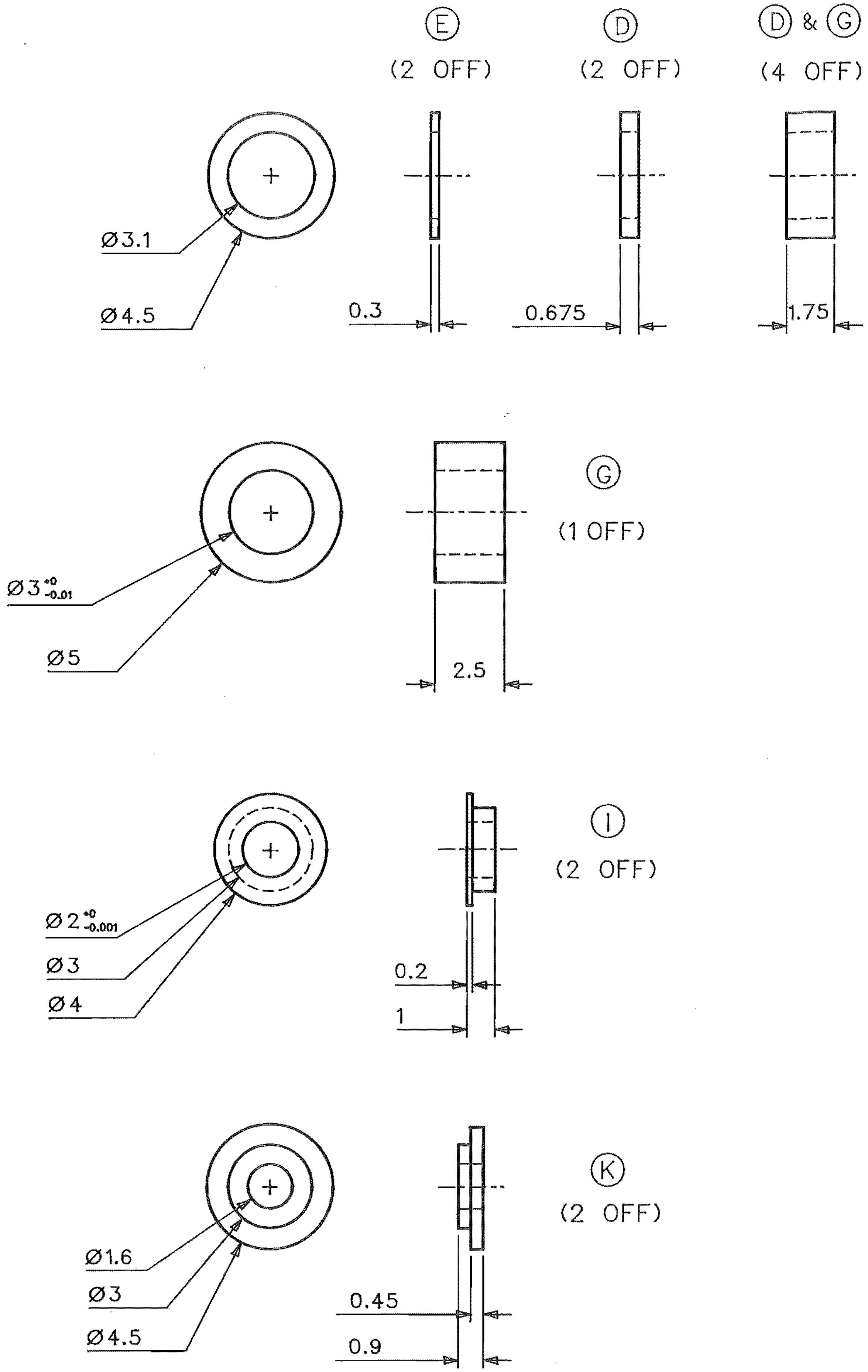


2. FINGER TIP SPACER BLOCK

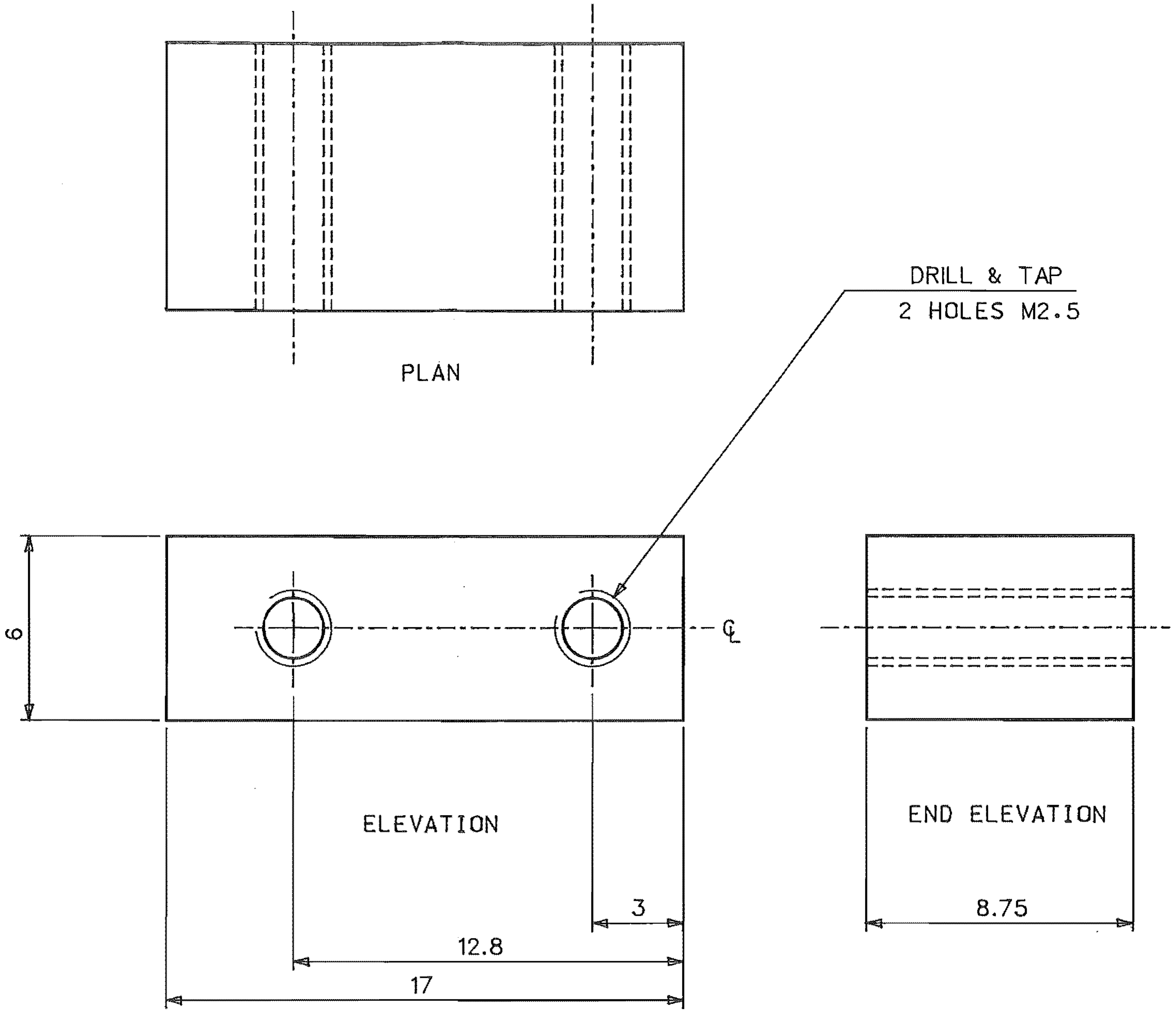
TOLERENCE : ID = ± 0.05
OD = ± 0.20 UNLESS OTHERWISE STATED

ITEM	DESCRIPTION	QUANTITY
2	SPACER WASHERS - Al OR 303 S/STEEL	AS MARKED
1	SPACER BLOCK - ALUMINIUM	1

ROHAND - PHALANGE SPACERS	SCHOOL OF ENGINEERING MECHANICAL ENGINEERING DEPARTMENT
SCALES : 5:1 APPROVED :	DRN : DEREK WARD; DATE : 06 DEC. 1994; DRG No : MK II - 002



1. PHALANGE SPACER WASHERS

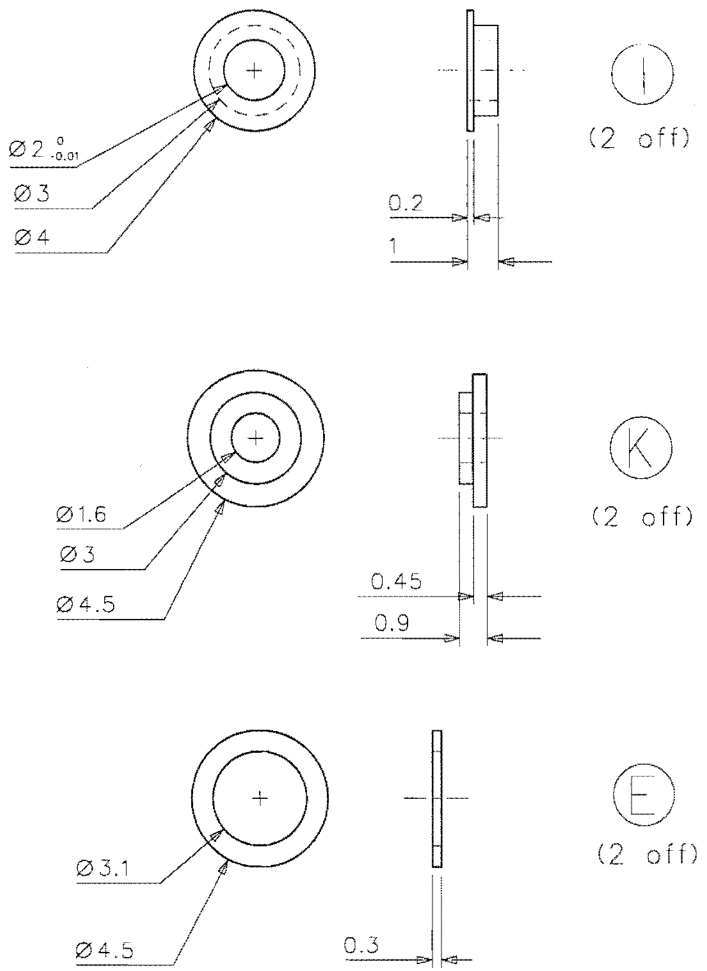


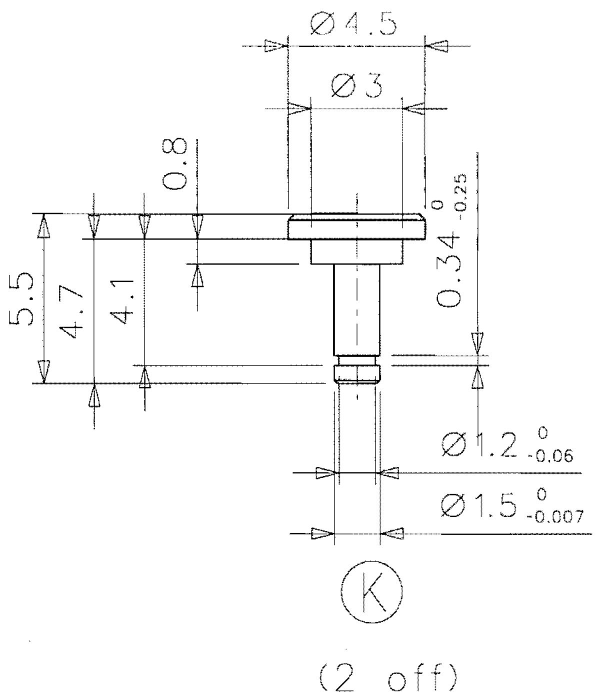
2. FINGER TIP SPACER BLOCK

ITEM	DESCRIPTION	QUANTITY
2	SPACER WASHERS - AI OR 303 S/STEEL	AS MARKED
1	SPACER BLOCK - ALUMINIUM	1

REV. A	ROHAND - PHALANGE SPACERS	SCHOOL OF ENGINEERING MECHANICAL ENGINEERING DEPARTMENT
	SCALES : 5:1 APPROVED :	DRN : DEREK WARD; DATE : 11 May 1995; DRG No : MK II - 002

TOLERENCE : ID = ± 0.05
OD = ± 0.20 UNLESS OTHERWISE STATED



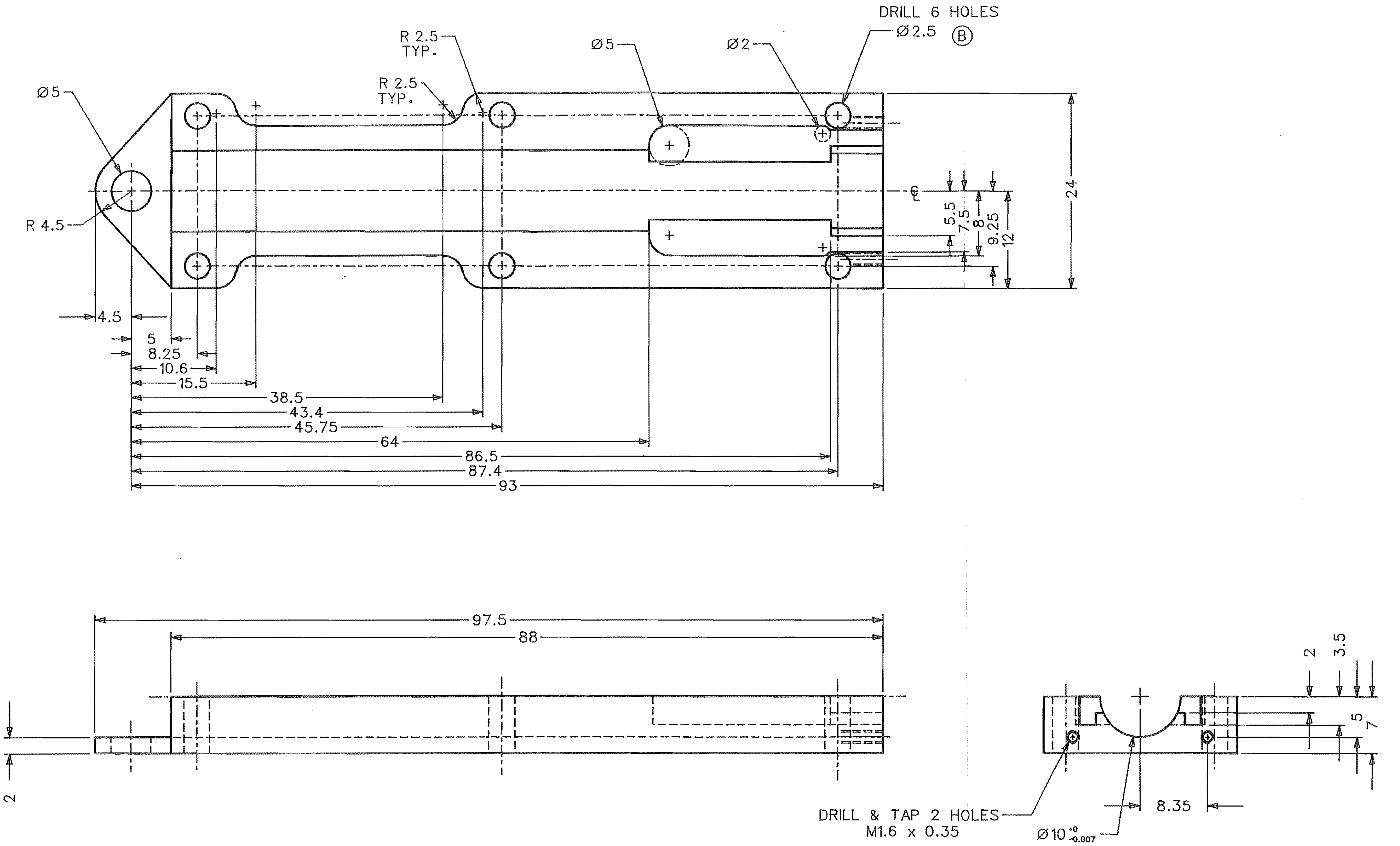


MATERIAL : 303 STAINLESS STEEL

MATERIAL : ALUMINIUM

TOLERENCE : ID = + 0.05
OD = + 0.20
UNLESS OTHERWISE STATED

ROHAND Modified Phalange Pins & Spacers		SCHOOL OF ENGINEERING MECHANICAL ENGINEERING DEPARTMENT	
		DRN : Derek Ward	DRG No : MK II-003
SCALES : 4:1	APPROVED :	DATE : 11 May 1995	



NOTE :

1. One block to be tapped M3 x 0.5 through 6 holes (B)

2. The other 3 blocks are to be drilled dia. 3.2 through the 6 holes (B) to clear the M3 button head capscrews.

ITEM	DESCRIPTION	QUANTITY
	M3 x 30 BUTTON HEAD CAPSCREW	6
1	CARPAL BLOCK - Tooling Grade Al.	4

ROHAND - METACARPAL BLOCK

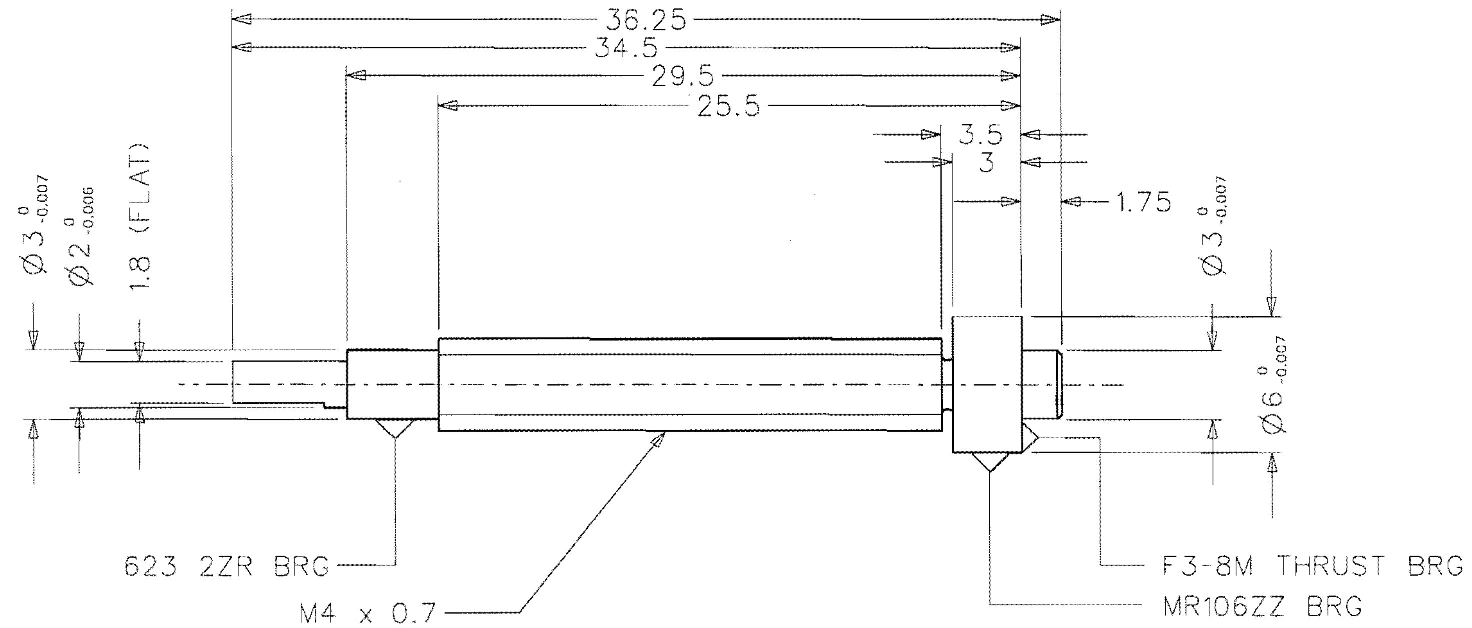
SCHOOL OF ENGINEERING
MECHANICAL ENGINEERING DEPARTMENT

SCALE : 2:1 APPROVED :

DRN : DEREK WARD

DATE : 31 AUG. 1995

DRG No : MK II - 004



NOTE :

1. Leadscrew thread is to be a neat fit in the nut (Drg 007) to reduce backlash.

2. A sharp edge at the LH end of the screw is essential to locate bearing.

ITEM	DESCRIPTION	QUANTITY
1	SCREW - 303 Stainless Steel	2

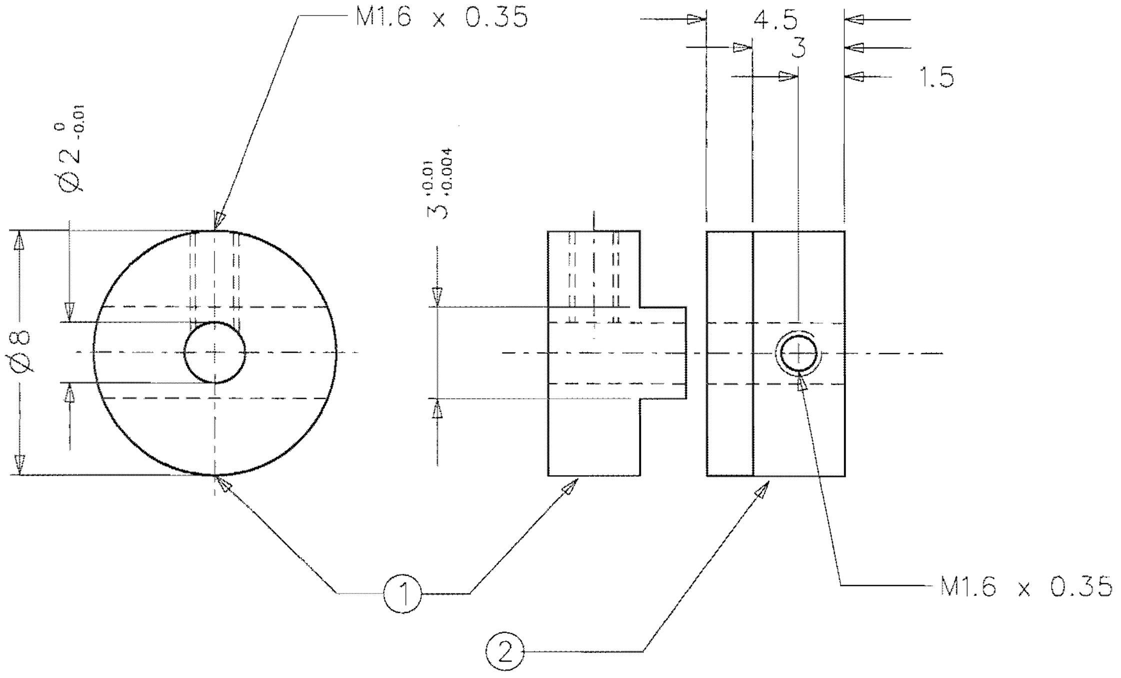
ROHAND - MAIN DRIVE SCREW

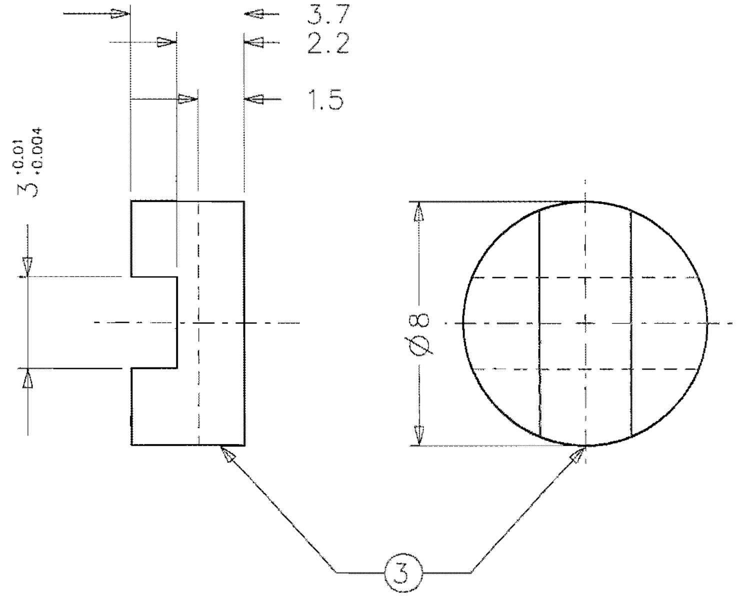
SCHOOL OF ENGINEERING
MECHANICAL ENGINEERING DEPARTMENT

SCALES : 3:1 APPROVED :

DRN : DEREK WARD
DATE : 29 AUG. 1995

DRG No : MK II - 005





NOTE : LEFT & RIGHT HAND HALVES ARE IDENTICAL BUT ARE SHOWN ROTATED HERE TO INDICATE ASSEMBLY

ITEM	DESCRIPTION	QUANTITY
4	GRUB SCREW - M1.6 x 3	4
3	CENTRE - Acetal	2
2	RIGHT HALF - Aluminium	2
1	LEFT HALF - Aluminium	2

ROHAND - FLEXIBLE COUPLING

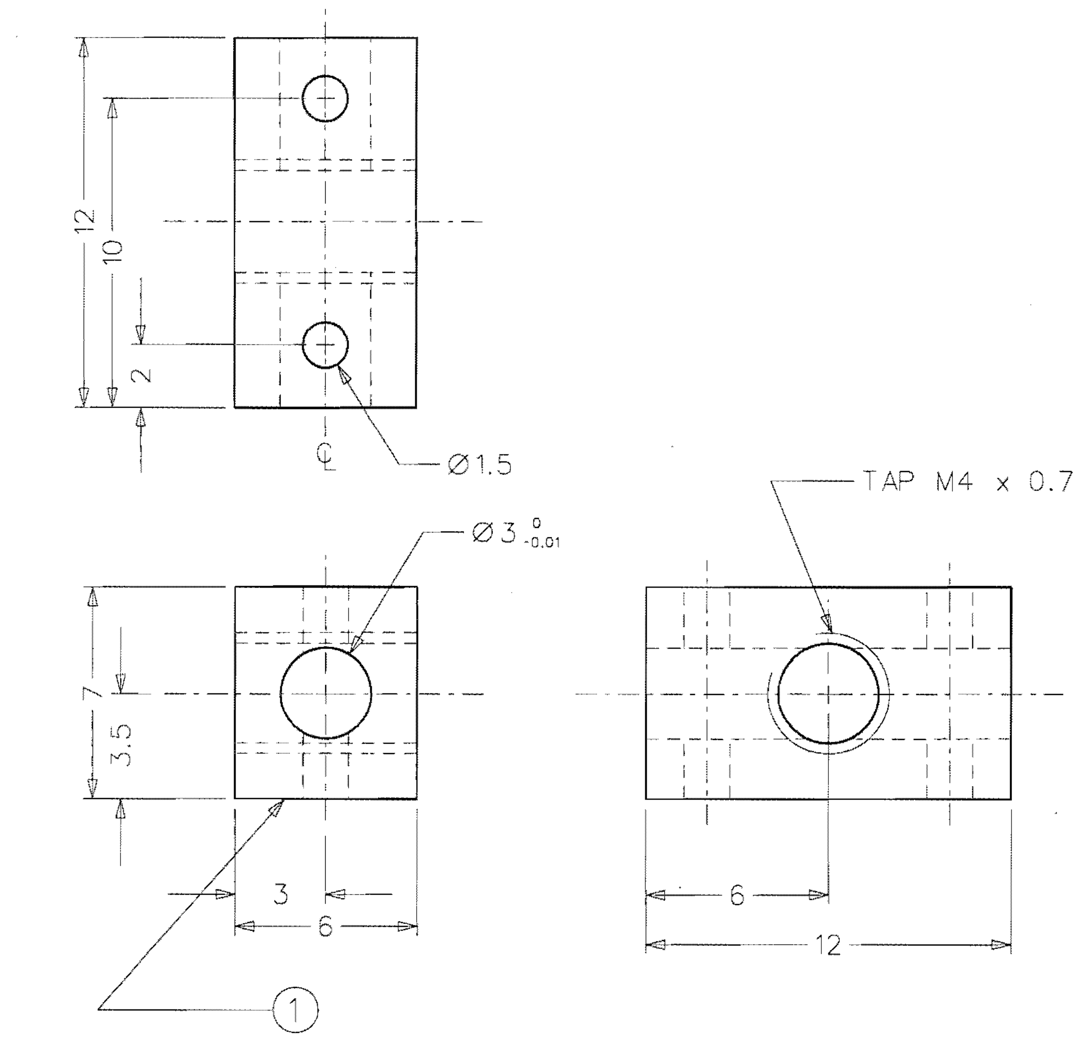
SCHOOL OF ENGINEERING
MECHANICAL ENGINEERING DEPARTMENT

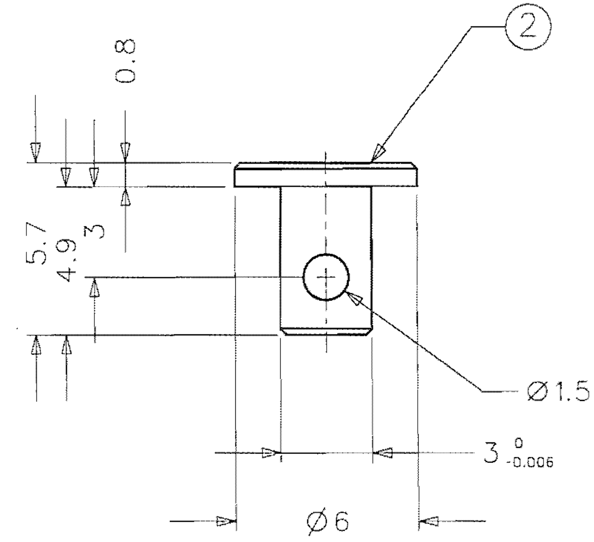
DRN : DEREK WARD

DRG No : MK II - 006

SCALES : 4:1 APPROVED :

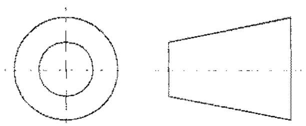
DATE : 08 NOV. 1995





NOTE : Nut is to be a neat fit between the 2 halves of the Carpal Body

ITEM	DESCRIPTION	QUANTITY
	ROLL PIN - 1.5 x 7	4
2	PIN - 303 Stainless Steel	4
1	NUT - Acetal	2



ROHAND - DRIVE NUT AND PINS

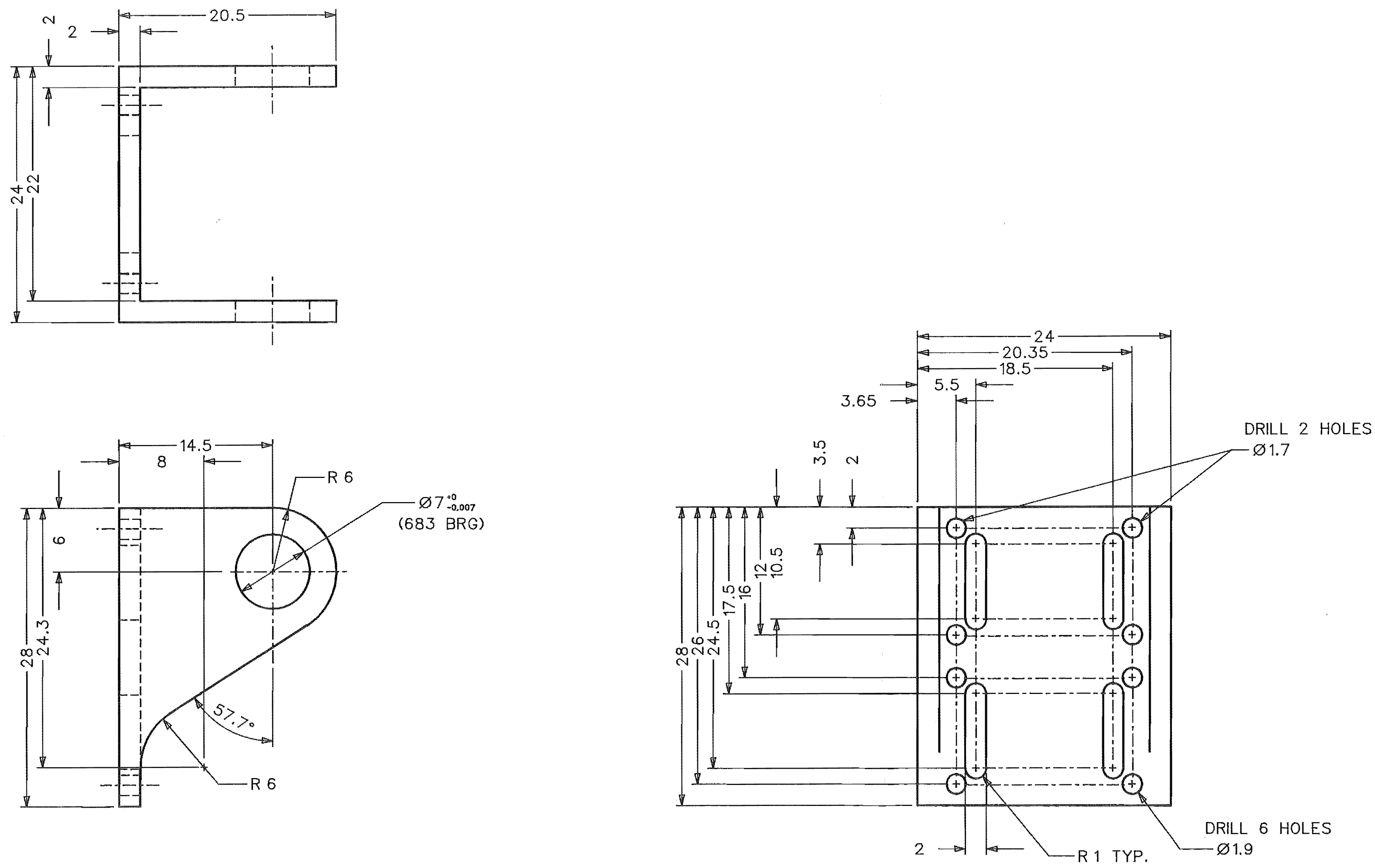
SCALES : 4:1 APPROVED :

SCHOOL OF ENGINEERING
MECHANICAL ENGINEERING DEPARTMENT

DRN : DEREK WARD

DATE : 30 AUG. 1995

DRG No : MK II - 007



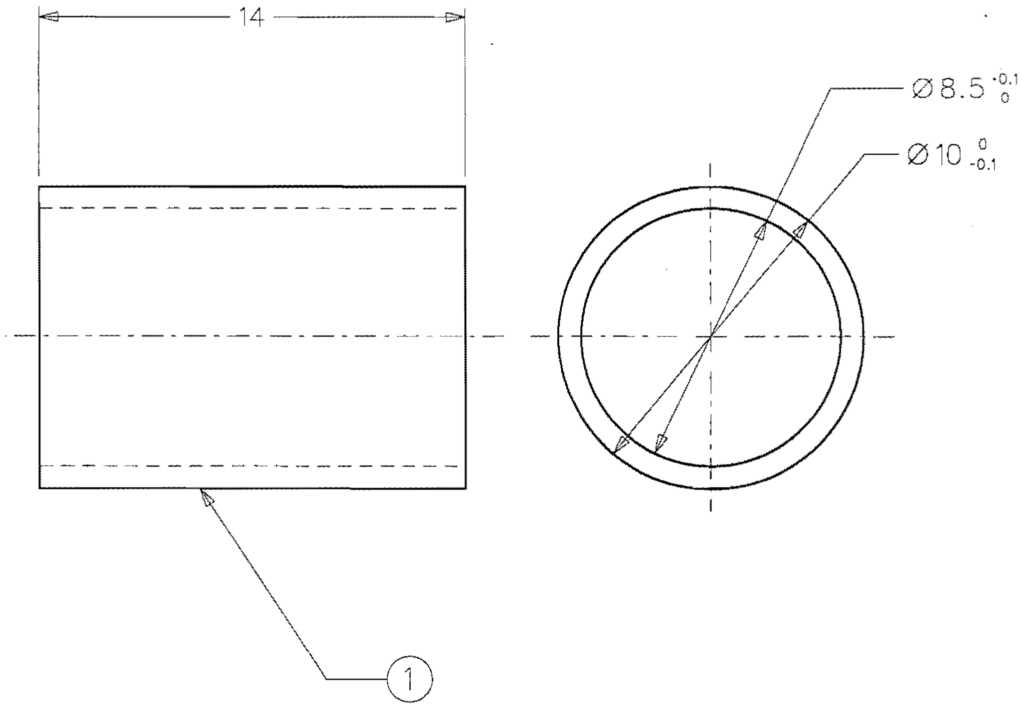
ITEM	DESCRIPTION	QUANTITY
	CAPSCREW - M1.6 x 4	8
1	END PLATE - Tooling Grade Al.	1

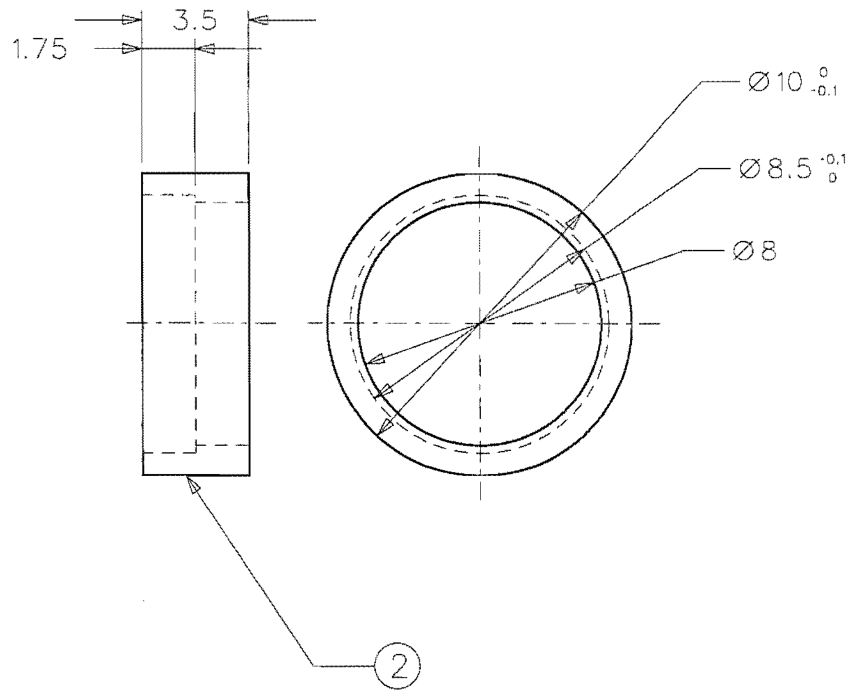
ROHAND
- PHALANGE SUPPORT BRACKET

SCALES : 2.5:1 APPROVED :

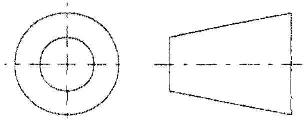
SCHOOL OF ENGINEERING
MECHANICAL ENGINEERING DEPARTMENT

DRN : DEREK WARD
DATE : 29 AUG. 1995
DRG No : MK II - 008

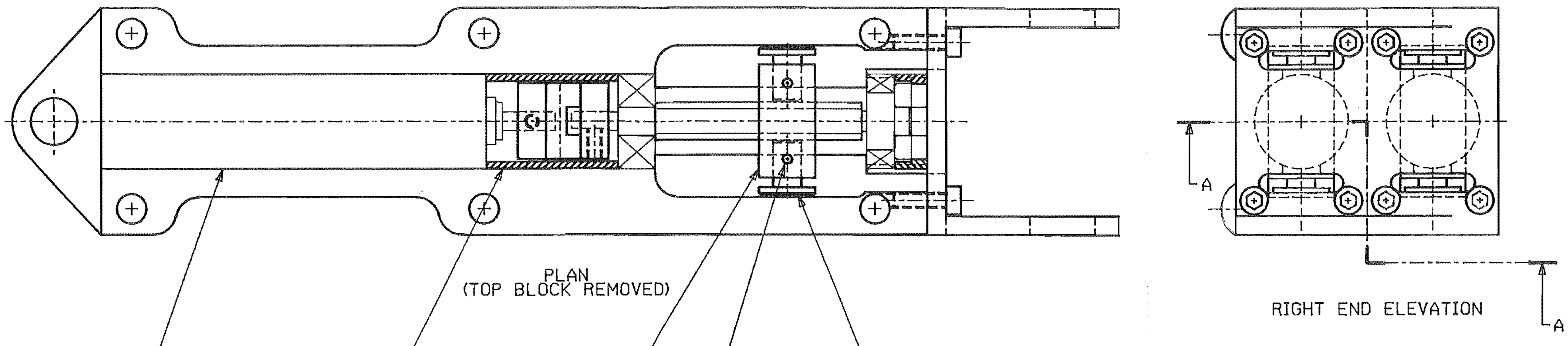




ITEM	DESCRIPTION	QUANTITY
2	THRUST BRG SPACER - Acetal	2
1	MOTOR END SPACER - 303 S/Steel	2

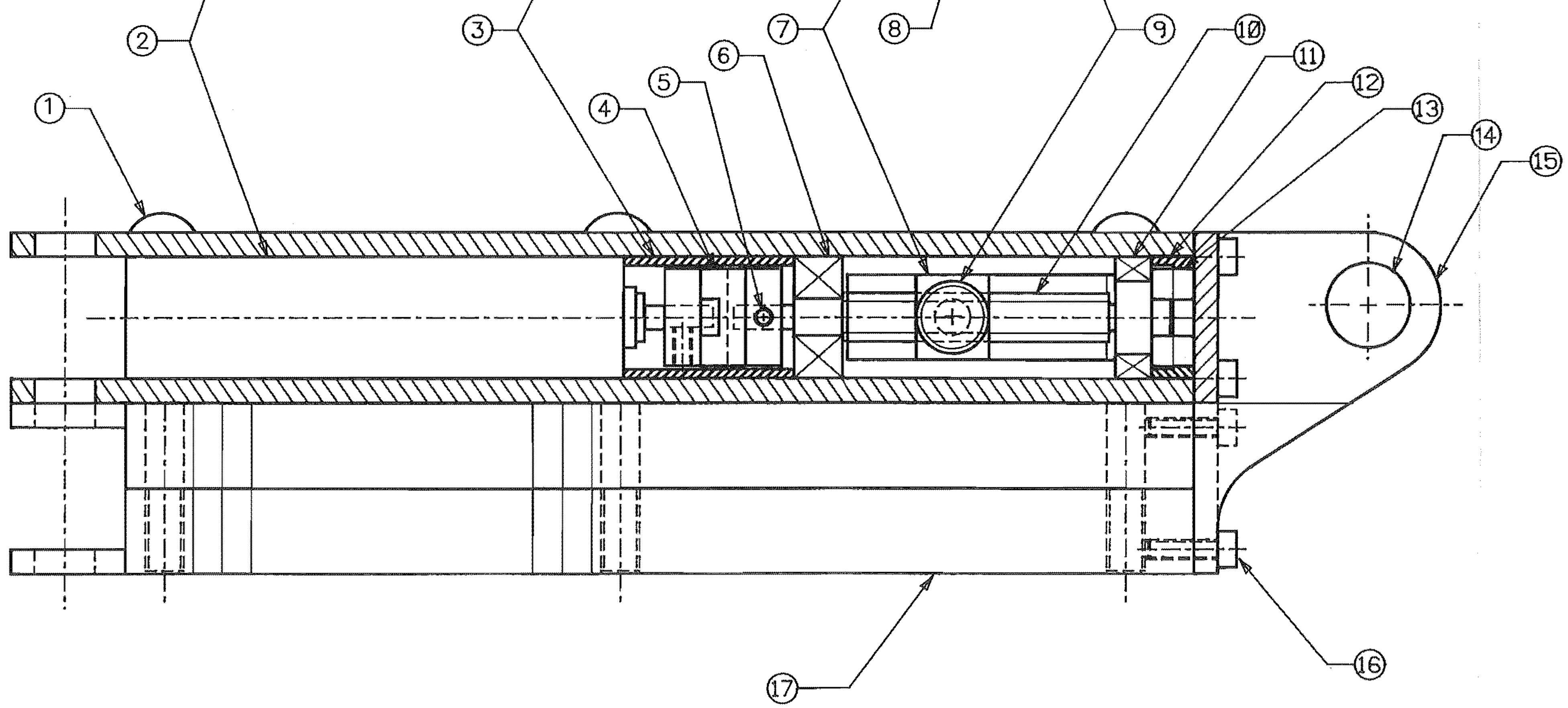


ROHAND - DRIVE LINE SPACERS	SCHOOL OF ENGINEERING MECHANICAL ENGINEERING DEPARTMENT	
SCALES : 4:1 APPROVED :	DRN : DEREK WARD DATE : 31 AUG. 1995	DRG No : MK II - 009



PLAN
(TOP BLOCK REMOVED)

RIGHT END ELEVATION



SECTION A-A

ITEM	DESCRIPTION	QUANTITY
17	CARPAL BODY - Ref DRG Ø03	4
16	M1.6 x 4 CAPSCREW	8
15	PHALANGE SUPPORT - Ref DRG Ø08	1
14	683 BRG	2
13	F3-8M THRUST BRG - Ref DRG Ø09	2
12	THRUST BRG SPACER	2
11	MR106ZZ BRG	2
10	SCREW - Ref DRG Ø05	2
9	PIN - Ref DRG Ø07	4
8	1.5 x 7 ROLL PIN	4
7	NUT - Ref DRG Ø07	2
6	623 2ZR BRG	2
5	M1.6 x 3 GRUB SCREW	4
4	COUPLING - Ref DRG Ø06	2
3	MOTOR/BRG SPACER - Ref DRG Ø09	2
2	MINIMOTOR ENCODER/MOTOR/G'BOX	2
1	M3 x 30 BUTTON HEAD CAPSCREW	6

NOTE : The BOTTOM Carpal Block is threaded M3 x Ø.5

ROHAND - ASSEMBLY DRAWING

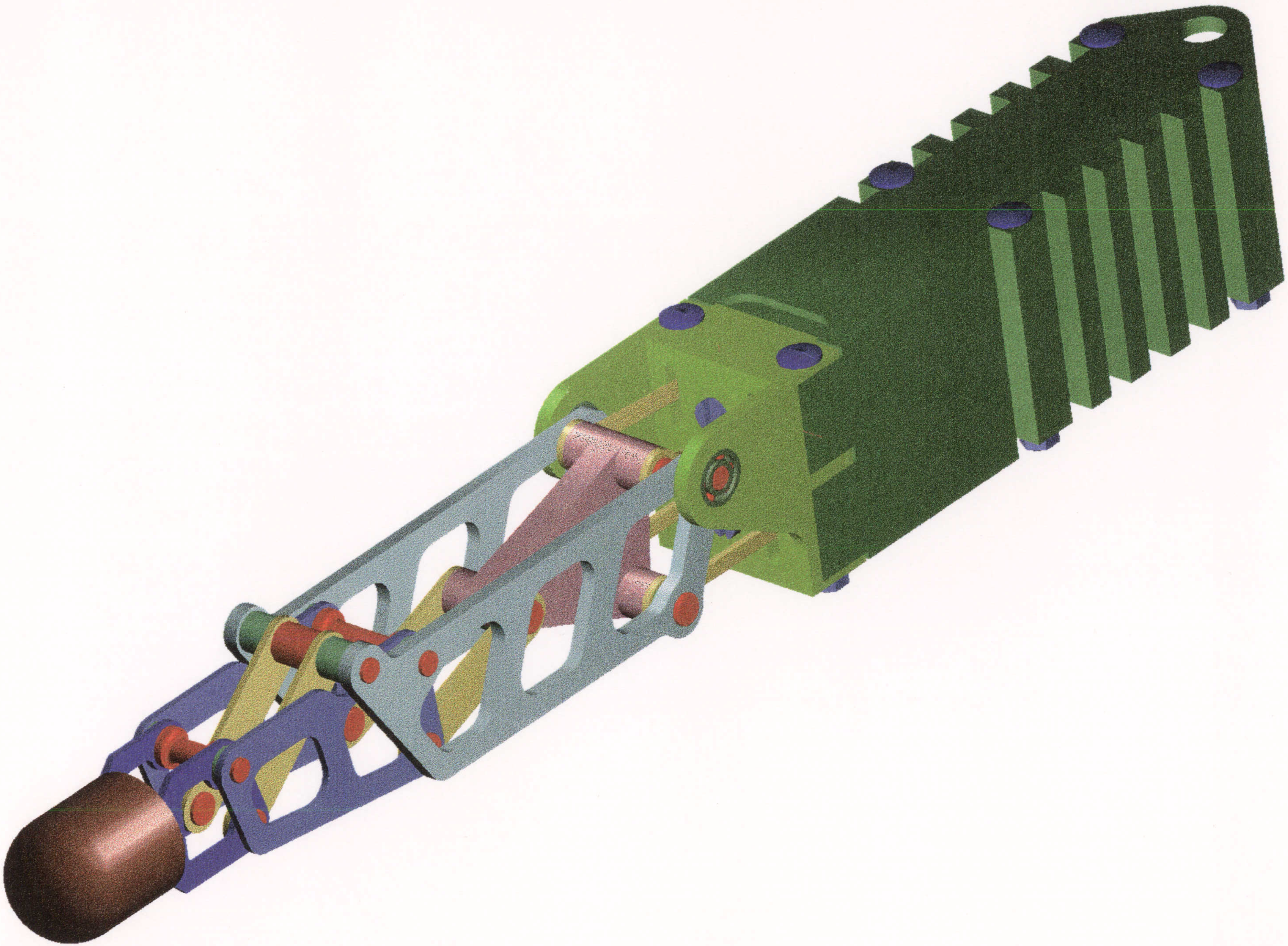
SCALES : 2:1 APPROVED :

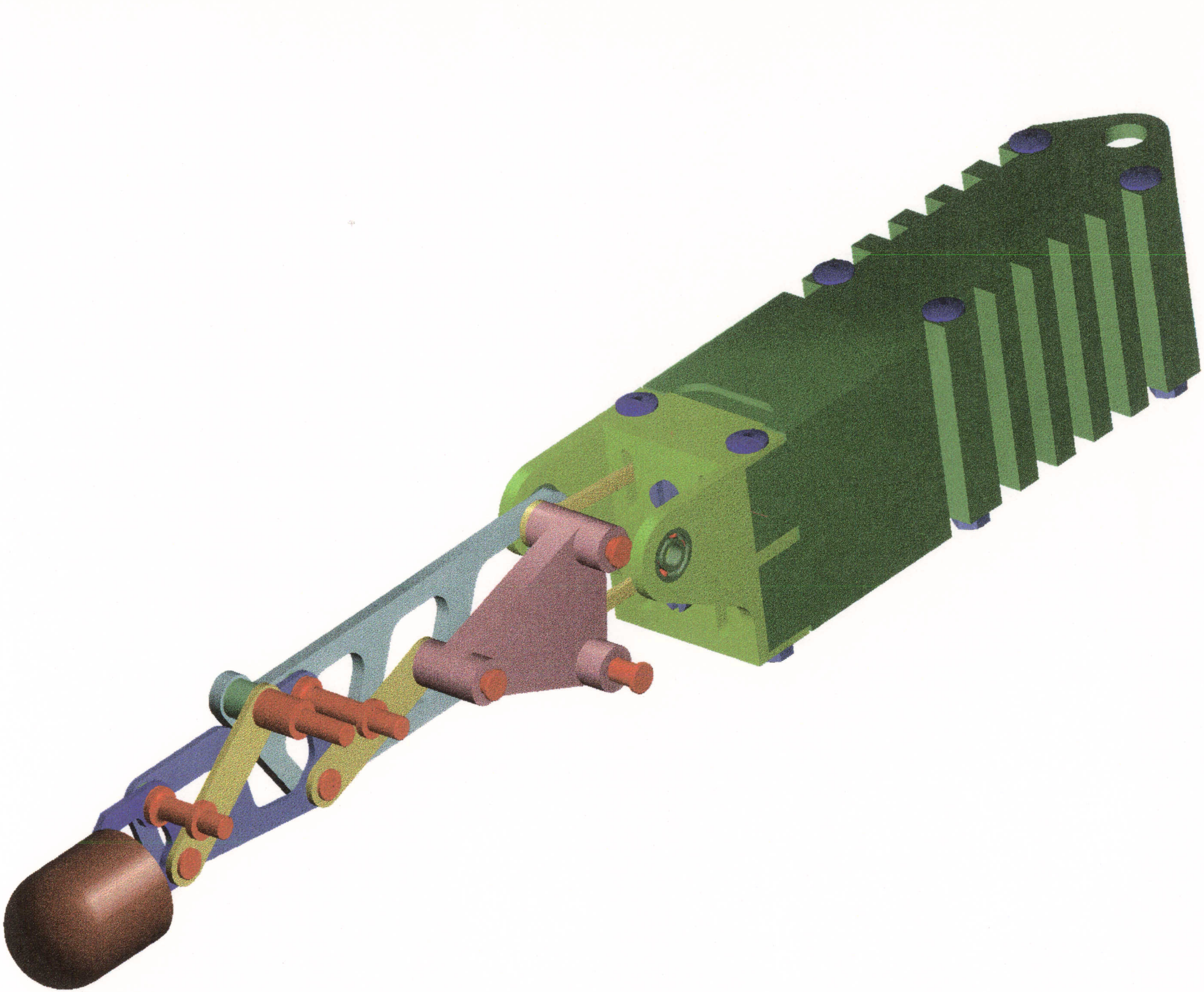
SCHOOL OF ENGINEERING
MECHANICAL ENGINEERING DEPARTMENT

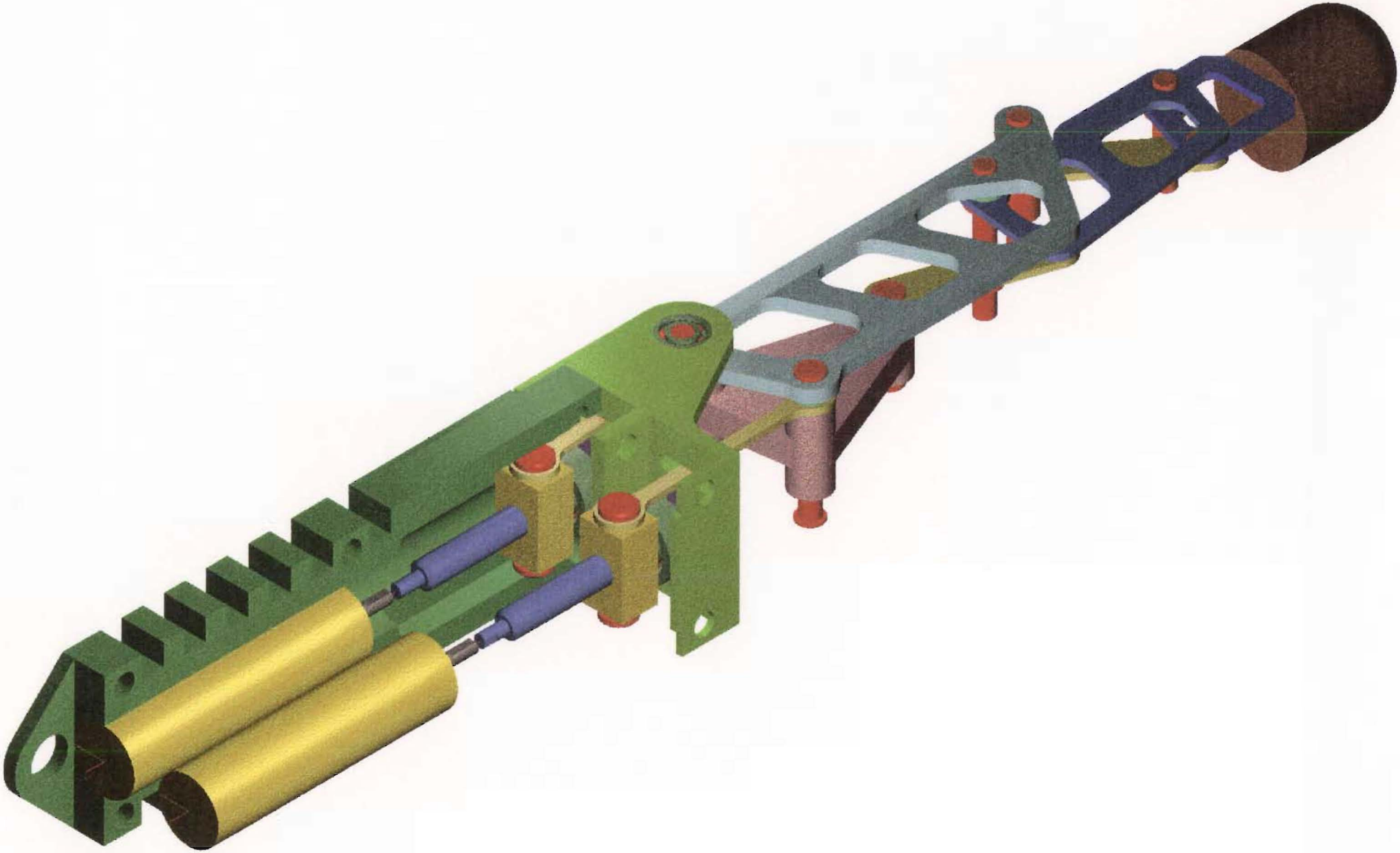
DRN : DEREK WARD
DATE : 31 AUG. 1995
DRG No : MK II - 010

Drawings

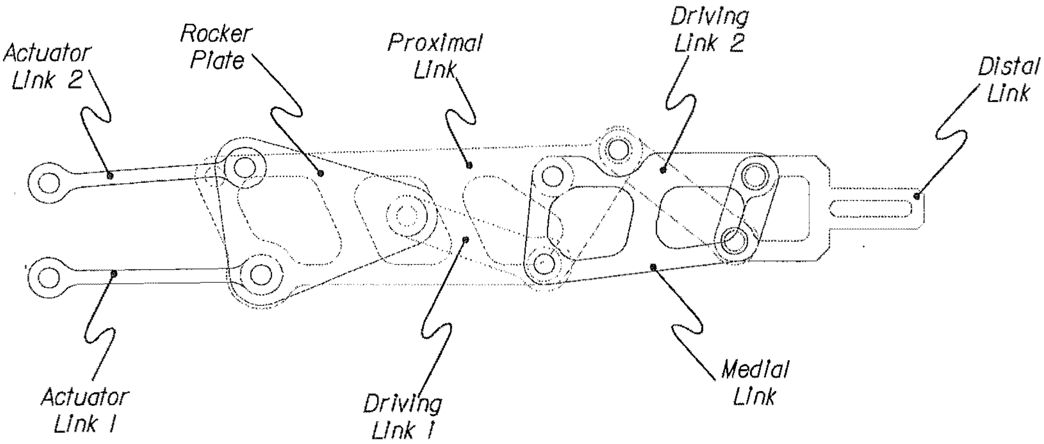
Number	Rev.		Date	Size	File	Ref. Files	Notes
MKII - 001		Phalange Pivot Pins	12 May. 1994	A3	PINS_DRG.DGN	DPHAL4.DGN	** still a 2 mm width error in pins **
-001	A	Phalange Pivot Pins	5 Nov. 1995	A3	PINS_DRG.DGN	DPHAL4.DGN	Drg. 001 with modified pins included ** still a 2 mm width error in pins **
- 002		Phalange Spacers	12 May. 1994	A3	SPAC_DRG.DGN	SPACERS.DGN	
-002	A	Phalange Spacers	5 Nov. 1995	A3	SPAC_DRG.DGN	SPACERS.DGN	Drg. 002 with modified spacers included
- 003		Modified Phalange Pin & Spacers	11 May 1995	A4	PIN_MOD2.DGN	SPACERS.DGN PINS_DRG.DGN DPHAL4.DGN	Modification of 001 & 002 because of incorrectly manufactured plates.
- 004		Carpal Body Block	31 Aug. 1995	A3	BLOCKOUT.DGN	BLOCK2D2.DGN	
- 005		Main Drive Screw	29 Aug. 1995	A4	SCREW.DGN	BLOCK2D2.DGN	
- 006		Flexible Coupling	11 Aug. 1995	A4	COUPLING.DGN	BLOCK2D2.DGN	
- 007		Drive Nut & Pins	30 Aug. 1995	A4	NUTNPINS.DGN	BLOCK2D2.DGN	
- 008		Phalange Support Bracket	29 Aug. 1995	A3	ENDPLATE.DGN	BLOCK2D2.DGN	
- 009		Driveline Spacers	31 Aug. 1995	A4	SLEVES.DGN	BLOCK2D2.DGN	
- 010		Assembly Drawing	31 Aug. 1995	A3	ASSEMBLY.DGN	BLOCK2D2.DGN	Shows assembly of power pack only

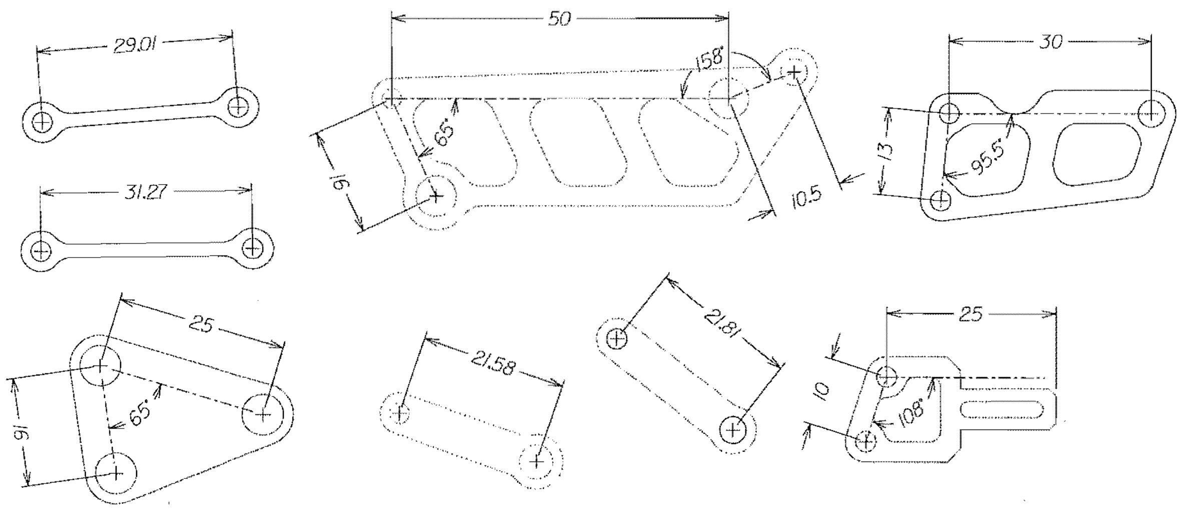






Basic Dimensions of Canterbury Finger Side Plates





Canterbury Finger Side Plates Laid Out for the CNC Mill